



Utilizing Marginalized Land for the Development of Symbiotic Waste-to-Energy Mini Grids in Remote Islands

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Utilizing Marginalized Land for the Development of Symbiotic Waste-to-Energy Mini Grids
in Remote Islands

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A Thesis in the Field of Sustainability
for the Degree of Master of Liberal Arts in Extension Studies

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Abstract

Remote islands face increasingly pressing constraints in their efforts to satisfy their waste management, energy, and water needs in a sustainable manner. Their small scale and isolated context restrict the availability of natural resources and infrastructure commonly available in mainland regions, which facilitates an adverse dependency on imports and exclusive use of landfilling. This thesis aims to investigate systemic solutions to the waste management, energy and water problems encountered by insulated communities. Analysis evaluates the benefits and costs of a novel network based on a waste-to-energy facility against the business-as-usual methods in the region of the Northern Aegean Sea in Greece. The economic, social, and environmental sustainability of the two systems is evaluated through a cost-benefit analysis, using a comprehensive set of economic, environmental, and social indicators. Two main alternatives were investigated; an ENERGOS gasification plant and an Enerkem waste-to-biofuels plant. Results show that the current system is economically and environmentally unsustainable and that substantial benefits are achieved through the development of the proposed network. The results also revealed that the possibility to produce biofuels is not only the most economically, environmentally and socially feasible alternative, but also fosters several synergies and the development of a circular economy at the regional scale. The results of the analysis facilitate prudent decision-making with regard to natural resource management in island regions and can be utilized by other groups of islands with similar waste generation levels and challenges.

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Chapter I

Introduction

Research Significance and Objectives

The lack of normal access to electric grids and infrastructure in remote islands perpetuates an overreliance on imported fossil fuels and the unsustainable management of natural resources, thereby necessitating the investigation of systemic solutions to facilitate a transition towards sustainable development and circular economy applications. This thesis aims to identify and assess integrated solutions to the waste management, energy, and water problems encountered by remote islands.

The results of the analysis will facilitate prudent decision-making with regard to natural resource management and can be utilized by other groups of islands with the necessary pre-requisites to foster similar developments.

The research objectives are:

- To investigate integrated solutions to increasingly pressing constraints such as waste management, energy and water needs in remote islands
- To develop a framework that can be utilized by other groups of islands with the necessary pre-requisites to foster similar developments
- To exemplify the need for trans-boundary synergies and facilitate prudent decision-making with regard to natural resource management in remote islands

Background

Problem Overview

Remote islands throughout the world face significant challenges on their path to sustainable development. Without normal access to electric grids and infrastructure, island communities historically struggle to identify optimal solutions to satisfy waste management, energy and water needs in an environmentally responsible manner. The lack of effective policies and integrated solutions hinders the development of innovative management, and perpetuates large-scale reliance on unsanitary and sanitary landfilling leading to significant environmental problems. In most of the islands, the problems are exacerbated by the lack of adequate space for landfills. Effective waste management becomes uniquely challenging and more convenient and cheaper alternatives, such as illegal burning and open dump disposal, proliferate in the absence of integrated solutions. Big island regions, such as the Bahamas, the Caribbean and the Northern Aegean, home to some of the most pristine biodiversity in the world and extensive tourism activities, rely on a significant number of unsanitary open dumps, jeopardizing their natural environments and sustainable development (Polido, João, & Ramos, 2014; Fielding, 2014).

Furthermore, islands are not connected to comprehensive mainland power grids and rely on outdated, inefficient diesel-powered power plants running on imported fuel, which also significantly contribute to greenhouse gas emissions. Island regions are the most import-dependent regions for petroleum products throughout the world (Jaramillo-Nieves & Del Rio, 2010; Polido et al., 2014). The Caribbean island states, Greece and U.S. Virgin Islands spend billions of dollars annually to import fuel to satisfy energy needs in their non-interconnected islands (Auth, Konold, Musolino, & Ochs, 2013; Davis, Haase, & Warren, 2011). As a result,

electricity prices are consistently rising. Hawaii's electricity rates are the most expensive in the United States, twice as high compared to the second state (U.S. Energy Information Administration, 2014), while electricity rates in Greek non-interconnected islands can be as much as eighteen times higher compared to average rates in the mainland (Regulatory Authority for Energy, 2015). These problems become particularly prominent in the summer months, when energy needs are amplified due to warmer weather conditions and the islands' tourism activity. Electricity and fuel demand regularly surpasses the grid's congested nominal capacity, resulting in blackouts costing millions of dollars (Shivakumar et al., 2014).

Other than energy, islands also rely on inefficient sources to satisfy water requirements. Island water resources are characterized by uneven chronic availability while population growth increasingly intensifies their demand (Gikas & Tchobanoglous, 2009). In the dry summer months, when water needs are the highest and amplified by tourism, island water availability is the lowest. Arid island environments, such as the Bahamas, and Barbados, rely on inefficient rainwater catchments or very costly and energy-intensive desalination plants (Polido et al., 2014), while Greece transports water by ships from the mainland, resulting in substantial costs and disruption risks (Gikas & Tchobanoglous, 2009), (Secretariat General for the Aegean and Island Policy of the Ministry of Maritime Affairs, Islands and Fisheries, 2015). Islands are also among the regions climate change will affect the most (Koutroulis, Tsanis, Daliakopoulos, & Jacob, 2013); increased droughts and rising sea levels exacerbate saltwater intrusion into freshwater resources (Polido et al., 2014). Water scarcity problems specifically are likely to increase in the near future, and when combined with forecasts of increased tourism activities and consequent water requirements, integrated solutions become a necessity.

Previous Research on Integrated Solutions to Island Sustainability Challenges

Even though the islands' unique sustainability challenges and multi-faceted vulnerabilities are well known, there is a dearth of research on integrated solutions and policies based on innovative waste-to-energy systems able to simultaneously tackle these pressing issues. Notwithstanding the wide range of natural and urban environments within the vast worldwide island networks, current literature and projects throughout the world predominantly focus on one technology and a particular issue at a time. More importantly little work exists on assessing their potential in developing symbiotic networks among islands and facilitating sustainable economic development.

Deschenes and Chertow (2004) reviewed the sustainability issues faced by remote islands and highlighted the necessity and applicability of symbiotic networks in island environments. Even though they promote islands as ideal models for integrated sustainability solutions, their scope of research was limited to specific small-scale industrial and manufacturing challenges faced by smaller entities in Puerto Rico and did not encompass the potential for wider synergies at the island scale or among groups of islands.

The Center for Industrial Ecology at Yale University conducted long-term research projects on island sustainability, with a particular focus on Hawaii and Puerto Rico. Although Eckelman and Chertow (2009) and Chertow and Miyata (2011) identified several opportunities for resource sharing and recommended synergistic solutions to Hawaii's sustainability challenges, these pertain only to small-scale individual entities. Even though waste-to-energy is applied as a method of burning waste, the island's incinerators are no longer able to cater to the island's increasing waste management needs (Chertow & Miyata

2011). Research, however, is not focused on investigating integrated solutions to facilitate widespread symbiotic developments throughout the island.

In St. Barthelémy, an incineration plant is linked to a desalination facility, but its inefficient incinerators run into the same roadblocks with regard to symbiotic developments as in Hawaii (Fielding, 2014).

Miranda and Hale (2005) state that island sustainability challenges should be examined simultaneously, but their research on integrated waste management and energy production solutions assessed a particular technology (waste incineration), and the solutions were not focused on identifying the potential for widespread symbiotic networks at the island scale. Even though they identify by-products and synergistic opportunities as critical factors that could enhance the competitiveness of similar developments, their limited cost-benefit analysis was based on market conditions that exist in mainland regions failing to assess the unique potential to develop markets and synergies in island environments.

In Malta and the Pacific Islands, proposed waste-to-energy developments face significant disruptions by communities who consider incineration facilities expensive, outdated and inefficient for establishing modern circular economies. Pirotta, Ferreira, & Bernando (2013) and Bohmer, Seidi, Stubenvoll, & Zerz (2008) investigated the potential of municipal solid waste for energy recovery in Malta. Their analysis focused on thermal treatment by incineration, which was stated as a necessity in order to reduce the amount of wastes, but not a potential foundation for symbiotic networks and circular economy applications. Furthermore, the cost-benefit analysis did not incorporate several critical environmental, social, and economic parameters.

Tavares, Zsigraiova, & Semiao (2011), and Zsigraiova, Tavares, Semiao, & Carvalho (2009) investigated the feasibility of waste-to-energy incineration applications in Cape Verde. Tavares et al.' (2011) analysis was limited to waste management, and regards waste-to-energy facilities as methods to increase efficiency, failing to consider synergies and integrated solutions. On the other hand, Zsigraiova et al. (2009) promote waste management and energy production as interlinked systems requiring simultaneous analyses to facilitate integrated solutions. Their research assessed the feasibility of an incineration plant that is linked to a desalination facility, although their brief environmental and economic assessment did not incorporate several social, environmental, and economic parameters and did not investigate the potential for synergies at the island scale. By focusing on optimizing transportation routes and the energy efficiency of waste management, Zsigraiova et al. (2009) missed several opportunities to investigate potential synergies within Cape Verde's widespread clusters of economic activity, as well as to identify innovative regional solutions that embrace the remaining neighboring islands.

Eckelman et al. (2014) conducted a critical review of island waste management practices around the world. Even though they analyzed more than 40 island cases and stated that the challenges facing island environments facilitate ample opportunities to identify alternative technologies and policies, their comprehensive review did not identify any projects or research on widespread integrated solutions and symbiotic networks at the island scale, or among islands. According to their research, synergetic island networks have reduced operating costs and environmental impacts, evident in cases such as Puerto Rico (Chertow, 2007) and Hawaii (Chertow, 2007). They conclude by promoting the need of integrated solutions to produce “actionable recommendations” in island environments, and specifically

highlight the lack of research and the multiple existing opportunities for synergetic networks to facilitate strategic decision-making.

Previous Research on The Greek Islands

Existing literature, and specific project assessments, for the Greek islands is even scarcer; synergetic integrated solutions based on innovative waste-to-energy management are absent and research is mainly focused on renewable energy opportunities (Xydis, 2013; Kaldelis, Gkikaki, Kaldelli, & Kapsali, 2012; Kyriakarakos, Dounis, Rozakis, Arvanitis, & Papadakis, 2011) assessing the technical feasibility of an incineration plant (Rodriguez, 2011) or investigating the benefits of combining renewable energy sources with desalination plants (Kaldellis, Kavadias, & Kondili, 2004). Most of this research is focused on making islands energy independent, overshadowing the remaining critical sustainability challenges, and little work exists on investigating integrated solutions that can provide solutions to multiple problems. Furthermore, the cost-benefit analyses performed by researchers lack objective data and neglect critical indicators that might significantly improve the economic, social and environmental feasibility of the proposed solutions.

Xydis' (2013) proposed solutions for 100% renewable energy systems and supergrids for islands in the North Aegean region focused solely on electricity production without investigating integrated sustainability solutions or potential synergies with the waste management and other existing regional economic sectors. Furthermore, analysis was focused on network design optimization to identify an ideal combination of technologies without assessing the economic, social, or environmental feasibility of the proposed applications.

Similarly, the multi-sector approach of Makropoulos et al. (2011) on integrated management systems for Agkistri discussed the island's waste management, energy and water supply problems independently without proposing integrated solutions. Furthermore, other than providing strategic recommendations, analysis was centered on implementing small-scale innovations that tackle specific aspects of the problems, without specifically focusing on potential synergies at the island scale or assessing the feasibility of the proposed solutions.

Kaldellis et al. (2012) and Kyriakarakos et al. (2011) illustrated the benefits of combining technologies to develop polygeneration grids for remote island locations, applicable to Agathonisi, a very small island, and at the household level, respectively. Both projects focused on a variety of energy and water applications that would match the target region's electricity requirements, failing to specifically integrate island scale waste management solutions and to investigate additional symbiotic opportunities. Furthermore, the evaluation methodology did not assess several economic, environmental, and social indicators, other than the primary investment requirements, jeopardizing the validity of any objective conclusions.

The recommendations of Zis, Bell, Tolis, & Aravossis (2012) for alternative waste management options for very small remote Greek islands did not consider integrated solutions or potential synergies among the group of investigated islands. Their research focused solely on comparing the financial feasibility of transporting all waste to the mainland against the current means of unsanitary open dump disposal, while the analysis lacked several environmental, social, and economic indicators to critically compare and consider additional potential options.

Skordilis' (2004) research on integrated solid waste management strategies for the island of Corfu disseminates the significant opportunities arising from waste management challenges in island environments when considering solid waste and by-products as a potential source of raw materials. Although waste incineration is discussed in the planning process, analysis criteria encompass qualitative strategic policy considerations dependent upon the local stakeholder's priorities. Research is limited on minimizing the environmental burdens of waste management, failing to further investigate the potential of resource utilization and synergistic solutions.

Ouzounoglou's (2014) recommendations for integrated waste management systems identified several opportunities for synergistic applications on the island of Naxos. Her research, however, focused on discussing the consequent policy implications of establishing small-scale waste management innovations without implementing quantitative analyses to assess their environmental, economic and social feasibility. The potential advantage of grouping the islands of the South Aegean region to facilitate synergies is investigated only through a policy-making perspective limited to the fact that the similar socio-economic context could accelerate the adoption of innovative solutions. Significant opportunities to integrate water and energy implications are missed, as well as the potential to achieve synergies and assess the potential benefit for the region.

The wide number and variety of Greek islands along with their scale and environments, however, allow for increased flexibility on the size and options of innovative technologies. Most of the Greek islands are not as large and remote as Hawaii or the U.S. Virgin Islands, and can also be combined into different groups based on their unique characteristics, consolidated renewable resource potential and proximity to smaller or larger

islands. Furthermore, Greek islands are home to considerable marginalized land areas – remnants from their past as industrial and economic centers- which can be utilized as a foundation for integrated solutions.

Even though several researchers, such as Eckelman et al. (2014) and Chertow (2007) state the problem of lack of scale faced by niche markets and technologies in island communities, no previous work exists on leveraging the potential for synergies among groups of islands in order to develop widespread innovative symbiotic networks, thereby circumventing the problem of diseconomies of scale. By applying Chertow's definition of industrial ecology- the synergies of water, energy, materials, and by-products across firms in geographic proximity (Chertow, 2007) to groups of geographically neighboring islands, the newly formed network can improve resource efficiency, reduce environmental burdens, waste production, and reliance on landfilling, as well as facilitate sustainable economic development collectively for the region (Zhu & Ruth, 2014). As such, scaling requirements can be overcome and large-scale incineration plants no longer constitute one-way inevitable solutions, facilitating the inception of unique distributed symbiotic networks.

This context makes the Greek islands an excellent subject for evaluation of integrated technologies to address these environmental challenges. By understanding the feasibility of the integrated solutions along with the specific requirements and influences of the consequent synergies, a novel framework can be developed to guide policy makers towards interdisciplinary approaches and regional resource utilization in island environments throughout the world.

Research Hypothesis and Specific Aims

This research is designed to examine the following hypothesis:

Distributed mini grids based on a waste-to-energy facility will help satisfy the waste management, energy, and water needs of a group of remote islands in the northern Aegean sea in a more sustainable manner compared to the business-as-usual approaches.

To address this:

1. An optimal waste-to-energy technology applicable at the island scale was established.
2. Symbiotic relationships with other sectors and natural resources at the island scale were identified.
3. The environmental, social, and economic benefits or costs of the innovative technical application and the business-as-usual system were assessed through a cost-benefit analysis.

Chapter II

Methods

Research Design

Research commences with the definition of the elements of the proposed technical application to briefly compare its advantages and disadvantages with other available innovative best practices applicable at the island scale throughout the world. Then, the required technical modifications to satisfy the waste management needs of a group of remote islands in the region of North Aegean, as well as potential ways of utilizing inputs and outputs to develop a symbiotic network that shares raw materials, resources and by-products at the island scale were specified. Next, a cost benefit analysis was conducted to compare the proposed development with the conventional practices and the environmental, social, and economic benefits and costs were evaluated.

Subsequently, the most important symbiotic pre-requisites were identified to review the potential of developing a framework to foster similar developments in other groups of islands in Greece or abroad. The research concludes with a discussion on implications for policy making.

Data Collection

Sources of data include primary data from the municipalities of Lesvos, Chios, Limnos and Samos, the Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, Limnos, Chios, and Samos, the Regional Waste Management Plan

for the Region of North Aegean, peer-reviewed journals, conference and workshop proceedings and presentations, reports from international organizations such as the International Solid Waste Association and United Nations Environment Programme, reports from European Union's research programs relevant to sustainable development such as Horizon2020, Greek national waste management and energy infrastructure legislation, reports from the Hellenic Solid Waste Management Association and relevant Greek ministries, as well as company brochures and whitepapers.

Literature used in this analysis is available online and can be accessed through common library systems. All primary data were gathered from both published and unpublished printed written documents. Reports from the local authorities are either available online, or were provided in printed form.

Methods

First, the group of Greek islands that serve as the case study were delineated and the critical socio-economic demographics, such as number of inhabitants, demographic growth, size and the environmental background, including land-use typologies, marginalized land and environmental pollution problems were briefly introduced. Data was primarily gathered from regional operational program reports for investments and growth submitted to the European Union, such as Reid, Komninos, Sanchez-P, & Tsanakas (2012) and Region of North Aegean (2013; 2014). The waste management, and energy production business-as-usual methods and regulatory frameworks were then reviewed, while primary data was gathered from the Intermunicipal Enterprise for Waste Management and Environmental Development, the Regional Waste Management Plan for the Region of North Aegean, municipal meetings and

association reports and literature to define the waste management, energy, water and raw material needs for the region of North Aegean. Figure 1 offers an illustration of the background analysis methodology.

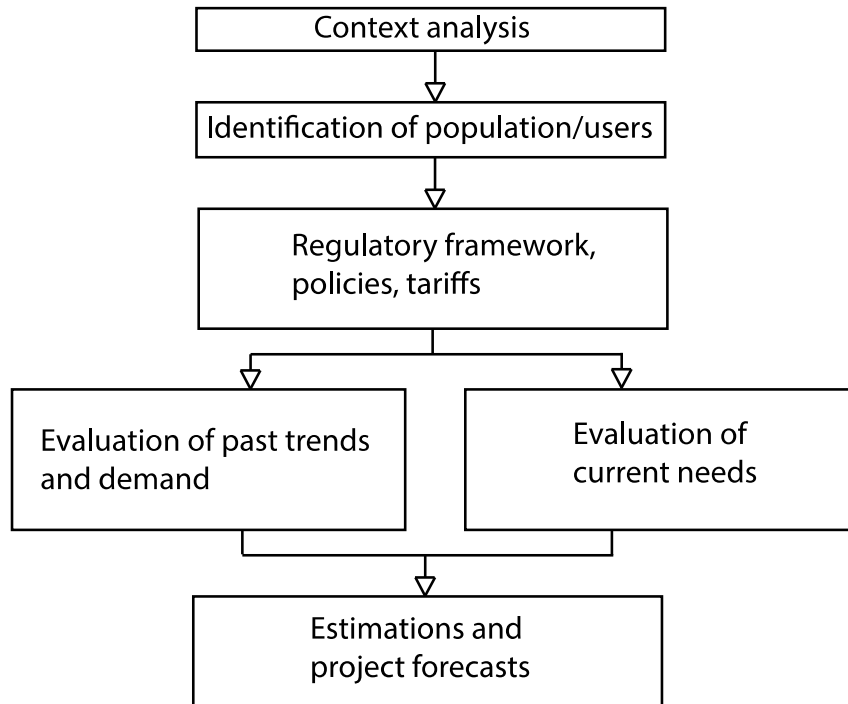


Figure 1. Case study background and demand analysis schematic.

In order to define the current municipal solid waste generation rates and management needs, the Regional Waste Management Plan as well as primary data acquired from senior officials of municipal solid waste management authorities in the region were reviewed. This enabled the estimation of the total daily quantity of municipal solid waste, as well as the total annual amount of waste produced in the region. Moreover, primary data from municipalities were used to identify and quantify the seasonal variation in waste generation due to tourism visits in the region. Specifically, primary data was gathered from the Intermunicipal

Enterprise for Waste Management and Environmental Development of Lesvos, the Intermunicipal Enterprise for Waste Management and Environmental Development of Limnos, the Municipality of Chios, and the Regional Waste Management Plan for the islands of Lesvos, Limnos, Chios, and Samos, respectively. Future annual waste generation rates were estimated in accordance with the Regional Waste Management Plan's estimates to accommodate the impacts of forthcoming waste management policy-making and population growth and material consumption. The Regional Waste Management Plan was reviewed to define the composition of municipal solid waste. Furthermore, self-reported data were compared with the Regional Waste Management Plan as well as reports from local administrations to check for uncertainties. Primary data were especially significant in the cases of Chios and Limnos, since the Regional Waste Management Plan underestimated waste generation from some specific municipal sources.

Annual energy generation, supply and demand statistics and data were gathered from the Regulatory Authority for Energy and the Operator of Electricity Market in Greece. A set of tables and figures was produced to visualize and present the key parameters and characteristics of the local waste management and energy systems.

Then, technical databases from company reports and white papers, presentations and literature were reviewed to define the proposed technology and the waste-to-energy facility. Two different plant designs were identified and compared: a design similar to an ENERGOS gasification facility and a design similar to an Enerkem waste-to-biofuels plant. Both proposed designs, including performance parameters and indicators, are based on currently operational plants. Estimates were sourced mainly from business planning documents and company presentations. The ENERGOS plant design was based on the Sarpsborg plant in

Norway (ENERGOS, 2015a) and compared with similar ENERGOS facilities throughout the world (Ellyin, 2012). The Enerkem plant design was based on the designs of Enerkem facilities in Alberta, Canada, and Prontoc, Mississippi.

The integral parts of the technical application were then presented and evaluated. The potential location of the proposed development was reviewed based on proximity to marginalized land and sources of largest waste generation rates and energy needs. The size of the proposed development was then modified to match the region's waste management needs.

The inputs, such as waste feedstock, and outputs, such as electricity, heat, renewable fuels, and by-products, of the proposed facility were evaluated to identify various ways they could be utilized by other entities, sectors or applications, such as renewable fuels for the local transportation sector and electricity and heat for nearby industrial and residential establishments. Then the regional context and scale was reviewed to identify additional symbiotic opportunities, and define the maximum feasible potential.

Literature, such as Jensen, Basson, Hellowell, & Leach (2012), Zhu & Ruth (2014), and other similar project examples that conducted GIS-based and technical analyses with relevant screening criteria and indices, such as potential for combined heat and power, industrial activity hotspots, energy production hotspots, wastewater hotspots, were reviewed to identify major sources and sites of industrial and economic activity able to facilitate symbiotic networks. Reviewing these enabled the assessment of the potential of entities and industries to participate in a network that share and exchange raw materials, resources, and by-products facilitated by the proposed development. Furthermore, this was used to establish the basis of environmental, social, economic, and technical indicators that could support and

facilitate the formation of similar symbiotic systems. Therefore, these formed the basic requirements, and the consequent policy-making implications, to develop a framework that can assist planning and policy-making in comparable island environments in Greece and abroad.

Two main scenarios were then designed. In the ENERGOS gasification scenario, waste is treated through gasification in order to produce electricity and heat, both of which will be utilized to provide renewable energy and heat to adjacent industrial and residential establishments. In the Enerkem gasification scenario, waste is treated through gasification in order to produce renewable biofuels and a small amount of electricity and heat. By-products produced throughout the gasification processes, such as water and char residues, will also be utilized to create additional revenue streams and synergistic opportunities. In both scenarios, synergies were established with the regional energy, agriculture, residential and construction sectors. In the Enerkem scenario, additional synergies were established with the regional water and transportation sectors. The potential for synergies with the region's natural and renewable resources, such as synergy with geothermal and hydrologic energy resources to enhance the application's potential combined heat and power capabilities for district heating or cooling networks, was also briefly discussed. Literature, such as Chertow (2007) and assessments of established symbiotic networks and circular economy applications, such as Jacobsen (2006), was reviewed to further examine possibilities for additional synergies and symbiotic links.

Data from company white papers, business planning documents, and presentations, were reviewed to estimate the investment, operation and maintenance costs of the proposed development. In order to facilitate an objective capital cost estimation and accurate

evaluation of the waste-to-energy facility, the plant's capacity (tons of waste per hour and then total treated amount per year) and the plant's overall availability (operational hours per year quantified as a percentage of operational hours to total hours in a year) were defined. As already mentioned, performance data and indicators are based on currently operational ENERGOS and Enerkem facilities throughout the world. The adopted project life-cycle period for both facilities in this analysis is 50 years starting immediately.

Then, the benefits from the potential symbiotic relationships were estimated by quantifying additional revenue streams and avoided disposal or operational costs by entities and sectors utilizing potential by-products, as well as other major sources of revenue, such as gate fees for waste management, and feed-in tariffs for electricity and heat sales. Other than the gate fees, electricity and heat sales as well as biofuels sales represent the main sources of revenue that were evaluated for both gasification scenarios.

Next, primary data from municipalities, local association reports, and literature were reviewed to estimate and quantify the performance parameters and environmental, social, and economic costs of the business-as-usual methods for waste management. A comprehensive list of quantifiable social and environmental externalities associated with the business-as-usual practices was incorporated, and the total economic cost of waste management, disposal and energy generation was evaluated. Primary data from the Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, the Intermunicipal Enterprise for Waste Management and Environmental Development of Limnos, the Municipality of Chios (2014; 2015), the Municipality of Limnos (2014), and the Regional Waste Management Plan were used to define the investment, annual operational costs and performance parameters, such as estimated remaining landfill years, of the waste

management facilities in the business as usual system. Landfill closure and rehabilitation cost data were gathered from Mpletsa (2014), the Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, as well as public meeting reports of the Regional Council of the North Aegean (Municipality of Chios, 2014). Closure and post-closure costs and maintenance needs were compared with international best practices stated in U.S. EPA (2014) in order to define an accurate capital estimation.

A spreadsheet model was then developed to assess and compare the environmental, social, and economic benefits and costs of the two systems. A cost-benefit analysis was conducted using established environmental, social and economic parameters to evaluate a comprehensive range of potential benefits and costs. In general, cost benefit analyses compare the economic feasibility of alternative scenarios by projecting the total costs and benefits over a specified time period of analysis, discounting them into present value, and ultimately evaluating the total net present value, the internal rate of return and the payback period. A chosen discount rate discounts future costs and benefits into present value, while the net present value is the total net cash flow of the project discounted to present value, the internal rate of return is the value of the discount rate at which the net present value is equal to zero, and the payback period is the number of years that the project requires to generate profits equal to its investment capital. Scenarios with a positive net present value are considered economically profitable, while the scenario with the highest net present value and internal rate of return, and the lowest payback period is the most economically feasible.

Figure 2 offers an illustration of the methodology of the cost-benefit analysis.

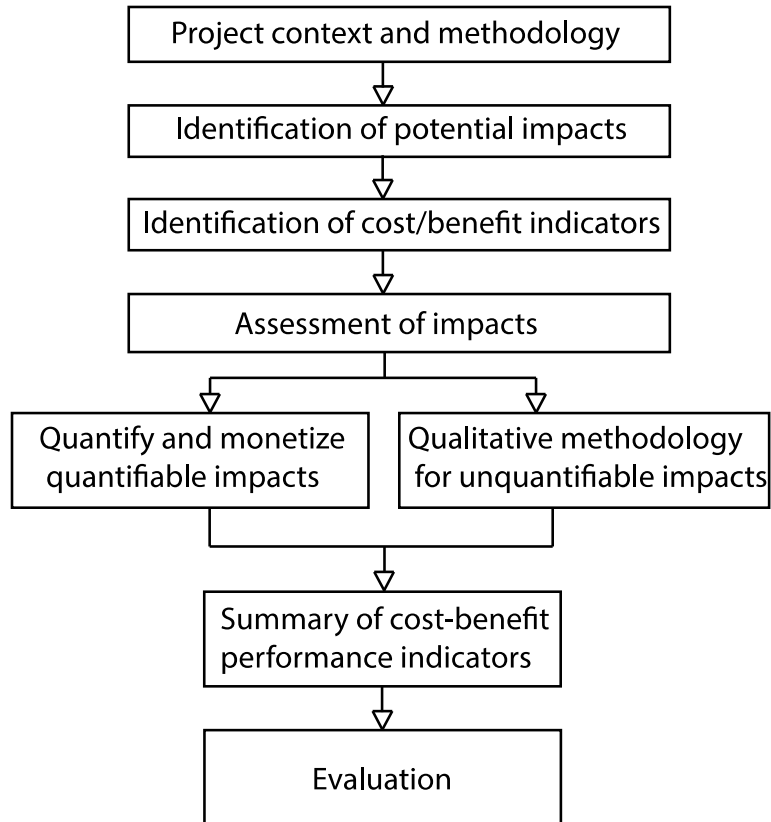


Figure 2. Cost-benefit analysis methodology.

The analysis was divided into three parts; financial, environmental, and social. The financial assessment evaluated the economic profitability of the systems, focusing on the aforementioned financial indicators. The assessment does not include any estimates and calculations regarding the financing capital structure of the projects. Although the model considers changes in inputs and outputs due to inflation, it does not take into account financing costs such as interests and debt repayments. It is estimated that approximately 18 months would be required for the construction of the plant, for both gasification scenarios, while landfill construction periods are not estimated in this analysis. An annual escalation rate of 3 % was used to capture changes due to inflation and a discount rate of 10 % was used

for the purposes of this analysis. Although it is a considerably higher number compared to discount rates used for similar projects and analyses in the European Union, it is necessary in order to fully capture the uncertainty of the financial domain in the region. Furthermore, the full effects of lower and higher discount rates are captured through sensitivity analyses.

The environmental assessment evaluated the environmental performance of the three systems. Several environmental parameters were quantified and evaluated, focusing on reductions in greenhouse gas emissions by recovered materials and energy, avoided landfilling, and reduced fossil fuel imports and usage, as well as benefits from reduced landfill disposal, including landfill space savings, avoided environmental contamination, and avoided costs for landfill decommissioning and remediation.

In addition to the financial and environmental analyses, the social assessment evaluated the social performance of the three systems. The social performance parameters used in this analysis include job creation, both during construction and the operational phase of the proposed developments, health benefits, including effects of avoided pollution on the quality of life of the people and damage to the local natural environments, and regional development, including regional laws, visual impacts, and effects on tourism development.

A best-case scenario was also evaluated by incorporating the additional revenue streams from the environmental and social analyses along with the potential effects of a carbon and landfill tax. This enabled the estimation of the maximum potential benefits for the region at large, when compared with the worst-case business-as-usual scenario.

All parameters and values associated with important performance factors of the analyses were estimated and monetized to facilitate an objective decision-making process. For parameters that are not easily quantified or monetized, indicators from comparable cases

in the literature were evaluated, implementing a similar approach to the benefit or cost transfer econometric methodology commonly used for the evaluation of environmental impacts. Greenhouse gas reductions or offsets were quantified and evaluated by assigning a cost of carbon. The carbon market price currently used in the European Union and Greece was used, along with a range of potential prices to limit uncertainty.

Actual, current market values in the region of North Aegean Sea were used for the price of water, electricity, heat, and by-products, while the time horizon of the analyses and the discount rates were chosen to appropriately reflect the short and long term socio-economic aspects of the proposed systems and related investments. Regulatory frameworks and primary data from the Regulatory Authority for Energy in Greece were reviewed to define the Power Purchasing Agreements for electricity and heat, while established market reports from reputable institutions and the U.S. Energy Information Administration (2015) were reviewed to define the average European biofuel prices.

The effects of potential policy changes, such as a ban on landfilling of biodegradable waste or higher renewable energy portfolio requirements, were not considered in the analysis or forecasts. Other than the gradual implementation of a landfill tax, which was investigated in the sensitivity analysis section, the currently adopted waste management, energy, and natural resource management policies and goals in the region of North Aegean remained unchanged for the duration of the analysis. Although such policy modifications are expected at the overarching European level to accelerate the shift towards a more sustainable energy system and landfill diversion goals, which would also greatly enhance the feasibility of the proposed solution, forecasting when and in what form these might be applied to the Greek islands is beyond the scope of this research.

Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the relative importance of potentially influential parameters on the economic feasibility of the assessed systems. In cases where parameters are influenced by factors that are hard to quantify or forecast, such as electricity prices or carbon taxes, sensitivity analyses provide low, average, and maximum limit estimates and scenarios, thereby incorporating a wide range of potential values and objective scenarios that make the assessed systems economically feasible and profitable.

The parameter values that were evaluated in this analysis are the discount rate of the project, a potential tax on carbon emissions at the European level, a tax on landfilling that is supposed to be implemented by the end of 2015, the combined effect of a tax on carbon emissions and landfilling practices, as well as the average market price of biofuels.

Research Limitations

There are several potential research limitations of this project. First, without comprehensive plans, this research alone will not be able to solve every island sustainability problem. Even though integrated solutions is a necessary first step, long-term sustainable natural resource management necessitates the implementation of several long-term policy changes and additional sustainability initiatives, such as energy efficiency measures, waste minimization and recycling endeavors. These will not be investigated or quantified in this research.

Moreover, there exists an inherent uncertainty and limitations when estimating and forecasting parameters that are dependent upon various external factors, such as fuel and technology costs. Therefore, these costs, including gasoline and gas, will remain constant for the purpose of this research, which might under, or over, estimate certain benefits or costs.

Best efforts notwithstanding, increased uncertainty is associated with the quantification of parameters that are not available or easily quantified. Even though the performance indicators are adopted from peer-reviewed literature, these are not able to adequately reflect the specificities and relative regional conditions of the case study. Given the islands' unique biodiversity and confined environments, benefits or costs are almost invariably different when compared to mainland or other island regions. Nevertheless, this is necessary in order to quantify impacts that would otherwise be impossible to include in the analysis.

Similarly, self-reported data and assessments by local associations and municipalities is an integral source for the evaluation of waste, energy and other island requirements. In order to account for the uncertainty over employed research and analysis methodologies, data were compared with peer-reviewed literature, when available, to maximize accuracy and facilitate objective conclusions. Otherwise, self reported primary data were assumed to be accurate.

Lastly, grid level technical effects, such as reduction of energy losses and grid stability impacts, and optimization were be quantified or investigated in this research.

Chapter III

Results

Case Study

Lesvos, Chios, Limnos, and Samos are located in the region of North Aegean, which contains a group of ten geographically dispersed islands in the northeast part of Greece (Figure 3). As illustrated in Table 1, with a total area of 3,430 km², these four islands are home to approximately 190,000 permanent residents, encompassing approximately 90 % of the region's total population and surface area (Hellenic Statistical Authority, 2011; 2014). Lesvos, the region's largest island, is the capital and the center of economic activity.



Figure 3. The Region of North Aegean (TUBS, 2011).

Although each island possesses unique socio-economic characteristics that collectively distinguish the region for its cultural and natural heritage, the relative importance of the main sectors of their economies remains largely the same (Reid et al., 2012).

Table 1. North Aegean island typologies and demographic characteristics.

Island	Permanent Residents	Area (km²)	Population Density (Resident / km²)	Max Altitude (m)
Lesvos	86,436	1,631	52.995	968
Chios	52,674	844	62.41	1444
Limnos	17,262	476	36.26	470
Samos	32,977	479	68.845	1443

As illustrated in Table 2, across the region, the tertiary sector accounts for approximately 85% of the Gross Domestic Product, and provides up to 70% of the total jobs, followed by the secondary sector, with 8.4% of GDP and 16.4% of jobs, and the primary sector, with 4.5 and 12% of GDP and jobs, respectively (Reid et al., 2012; Region of North Aegean, 2014). Tourism and the service sector are the traditional epicenters of the economy (Reid et al., 2012), while businesses consistently encounter the inherent problems of insular communities, such as the difficulty in expanding and achieving economies of scale (Reid et al., 2012; Region of North Aegean, 2014). Although both tourism and trade sectors are particularly affected by seasonality, since a considerable proportion of the jobs is part-time and thus seasonal, they represent by far the largest regional contributors to both GDP and

jobs. Notably, Lesvos and Chios also have advanced real estate, renting, and other financial services sectors (Reid et al., 2012).

Table 2. The regional economy of the North Aegean.

Sector	GDP (%)	Jobs (%)	Comments
Primary	4.6	13.3	Small private agricultural, livestock and mixed-use farms and holdings.
Secondary	8.4	16.4	Construction, manufacturing, processing.
Tertiary	85	71.3	Real estate, tourism, trade.

The region's distinct cultural heritage, along with its pristine natural environment, attracts a considerable number of tourists throughout the year. According to the Annual Tourism Census, more than 1.5 million tourists visited the region for at least one night in 2013 (Association of Greek Tourism Enterprises, 2015). During the periods of the highest tourism activity, seasonal residents often account up to 30 % of the permanent resident population, which further exacerbates the pressures on infrastructure and the surrounding environments. As such, the biggest islands in the region face regular water shortages and energy outages (Region of North Aegean, 2014).

The region is home to some of the most significant and unique natural environments in the Mediterranean basin. Critical ecosystems and areas designated under the Sites of Community Importance and Special Protection Areas categories of the NATURA 2000 network exist throughout the islands (Region of North Aegean, 2014). Furthermore, unlike other Greek island regions, such as the Cyclades, the region of North Aegean contains

considerable areas of forests. As illustrated in Figure 4, forests, and agricultural areas represent the main categories of land use in the region.

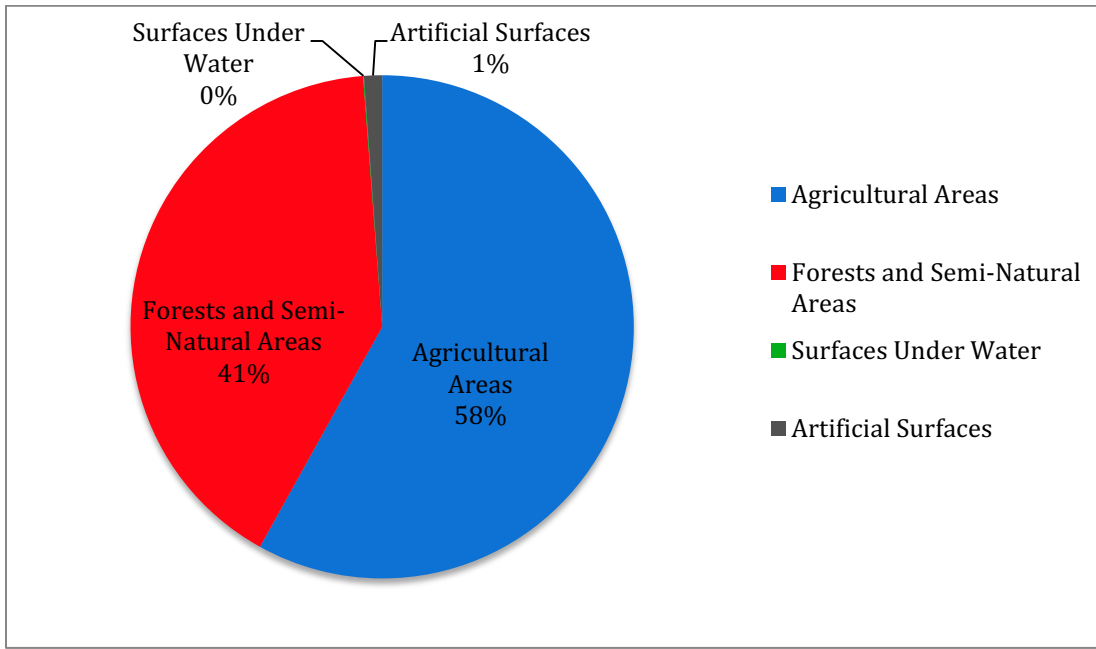


Figure 4. Land use typologies in the region of North Aegean.

Despite the significance of their natural and socio-cultural environments, the small scale and isolated context of the islands restrict the availability of natural resources. Particularly critical is the lack of fossil fuel resources, which forces the region to rely extensively on imports to fuel its economy. The industrial sector is especially affected by the lack of resources and the high price of energy, which tends to restrict industrial development and hinder productivity (Region of North Aegean, 2014). Adequate land for widespread agriculture is limited, while critical industrial supplies, fossil fuels, and other natural resources and minerals have to be imported from neighboring mainland regions, usually at a

very high cost, which historically hinders the potential for sustainable development throughout the region (Reid et al., 2012; Region of North Aegean, 2014).

Although the region of North Aegean is classified among the least-developed regions in the European Union (Eurostat, 2015a), significant potential exists for sustainable resource management and utilization, which can enhance economic development prospects and foster the development of a regional sustainable hub. Currently, businesses and sectors are dispersed throughout the region and small in scale (Region of North Aegean, 2014), while synergies and cooperation among different entities and sectors is not pursued. Insularity along with the lack of resources and reliable infrastructure affect productivity and hinder the development of economies of scale (Region of the North Aegean, 2014), which oftentimes are fundamental in order to drive productivity and sustainable growth.

The region has prepared several long-term plans for investments and regional growth (Region of North Aegean, 2013), however, the potential for collective solutions based on synergies, regional resource utilization and extensive cooperation in order to reduce production and operational costs, and achieve enhanced resource efficiencies and economies of scale is either not identified or not promoted. This problem is particularly evident in the case of renewable energy, transportation, waste and wastewater management (Region of North Aegean, 2014).

More importantly, the regional plans do not account for or promote the potential for cooperation and synergies among the islands of the North Aegean region in order to establish collective solutions at the regional level. Table 3 presents a basic overview of the most prominent challenges and opportunities in the region of North Aegean.

Table 3. Challenges and opportunities in the region of North Aegean.

	Challenges	Opportunities
Physical	<ul style="list-style-type: none"> • Lack of natural resources • Lack of infrastructure • Unsustainable waste management practices • Expensive and polluting energy generation • Large seasonal variations in energy and water demand –water shortages for irrigation 	<ul style="list-style-type: none"> • Establishing unique economies of scale to drive efficiencies • Opportunities for co-processing to minimize costs • Opportunities for new innovative ways to utilize waste and natural resources
Institutional	<ul style="list-style-type: none"> • Lack of regional cooperation • Small, dispersed sectors 	<ul style="list-style-type: none"> • Significant potential for synergies among and within islands • Interconnection of production processes of sectors

Marginalized Land

The region has traditionally been known for its widespread extractive and industrial activity, particularly for the presence of several massive marble and igneous rock quarries (Ministry of Environment, Energy and Climate Change, 2013). Although large-scale mining and industrial developments have gradually moved over towards more accessible regions in mainland Greece, several establishments remain operational throughout the region.

Moreover, former industrial establishments are commonly found in close proximity to population centers, which usually consist of old port facilities, small abandoned airports and army facilities, as well as abandoned factories. These facilities are currently unutilized.

Seasonal and Informal Population Dynamics

The region's extensive tourism activity significantly increases the total population numbers throughout the year, especially during the summer months. As presented in Table 4, according to the Annual Tourism Census, approximately 1.5 million tourists visited the North Aegean region in 2013 (Association of Greek Tourism Enterprises, 2015). Although this estimate does not include second house owners and seasonal workers, the total number of tourists exceeds the total number of permanent residents by more than fifteen times. The periods of highest tourism activity were summer, with 54% of total visits, followed by spring, with 26 % of total visits, autumn, with 13% of total visits, and the winter months with 7 % of total visits. This highly dynamic influx of people introduces considerable additional requirements for natural resources, energy and waste management.

Table 4. Annual visitors in the region of North Aegean in 2013.

Period	Visits (%)	Total Visitors	Daily Visitors
January – March	7	104,000	1,155
March – June	26	387,000	4,310
June – September	54	805,680	8,952
September – December	13	193,960	2,155

Furthermore, the informal population has been constantly rising. Recent geopolitical events and social unrest are exacerbating migration flows from the Western coasts of the Middle East and the wider Eastern Mediterranean region, thereby creating substantial inflows of people. According to the local authorities, approximately 400 to 800 migrants have been arriving across the region on a daily basis (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, personal communication, July 22, 2015). The United Nations Refugee Agency (2015) estimates that approximately 80,000 to 170,000 people have arrived during the last eight months. Although most of the migrants are eager to leave the islands and move towards the northern parts of Greece, it is currently unknown whether they do leave as soon as possible or whether they stay for longer periods.

Waste Management in the Region of North Aegean

Historically, the Northern Aegean islands have faced significant waste management challenges. Open dump disposal proliferated in the absence of integrated waste management plans, and the region has a long history of attracting negative publicity for the lack of environmental management and the consequent environmental impacts (Ministry of Reconstruction of Production, Environment and Energy, 2014). Specifically, more than one hundred open dumps remained active for several decades, leading to considerable environmental, social, and economic impacts and perturbations, oftentimes among the most pristine natural environments. According to the regional authorities, the first comprehensive regional waste management plan was enacted in 2005 (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, personal communication, July 22, 2015). At that time, the region relied solely on approximately 120 operational open dumps

for waste disposal. Every major population center throughout the region had its own open dump, where waste was disposed of and oftentimes burned (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, personal communication, July 22, 2015). In total, more than 400 acres and more than 1,000 cubic meters of land have been lost through open dump disposal throughout the region, while more than \$30 million have been reserved in order to revitalize those areas. Lesvos alone has spent more than \$10 million in order to restore its open dumps during the last decade (Mpletsa, 2014).

Despite the significant recent efforts to close down and restore open dumps and unsanitary landfills some open dumps remain operational and landfill disposal is the exclusive means of waste management (Region of North Aegean, 2015). Four sanitary landfills are currently operational throughout the region, located in the four largest islands of focus. Table 5 presents an overview of the disposal methods in the region of North Aegean.

Table 5. Municipal solid waste management in the region of North Aegean.

Island	Waste to Landfill (%)	Recycling (%)
Lesvos	99.8	0.02
Limnos	99.1	0.09
Chios	97	3
Samos	99.9	0.01

Landfill disposal, however, is the least preferred municipal solid waste disposal option in the European Union, while unsanitary open dump disposal is prohibited and heavily penalized (Council Directive 2008/98/EC, 2008). As such, Greece has been the target of

substantial fines for unsustainable waste management practices multiple times over the last decade (European Commission v. Hellenic Republic [2013] C-378/13). The latest infringement mandated both the immediate closure and restoration of operational unsanitary open dumps, especially the ones that are located next to pristine natural environments. In addition to a total fine of approximately \$11 million applied at the national level, regions with operational unsanitary open dumps are forced to pay \$45,000 for each operational open dump, every six months (European Commission v. Hellenic Republic). Consequently, the region of North Aegean is faced with considerable additional costs because of its unsustainable waste management practices.

Other than small-scale recycling facilities, which primarily target packaging and paper waste (Region of North Aegean, 2015), the region currently lacks advanced municipal solid waste treatment facilities (Region of North Aegean, 2015). Additionally, these facilities are currently able to accommodate waste produced by just 30% of the total population (Ministry of Reconstruction of Production, Environment and Energy, 2014; Region of North Aegean, 2015). Consequently, although recycling is the top priority with regard to solid waste management, the region has been unable to recycle large amounts of materials. As illustrated in Table 5, currently, recycling accounts for less than 1% of total municipal solid waste generated throughout the region. On the other hand, the waste transfer network is highly developed, and waste from every community throughout the region can be disposed of safely in a timely manner. Most major islands have transfer and pre-treatment stations for recyclables and municipal solid waste, while ships are used to transfer municipal solid waste and recyclable materials from smaller and least developed islands, to larger ones. Table 6

presents an overview of the municipal solid waste management facilities in the region of North Aegean.

Table 6. Waste management facilities in the region of North Aegean.

Island	Landfills			Transfer Stations
	Facilities	Construction	End of Life	
Lesvos	1	2009	2029	5
Chios	1	2013	2033	2 (1 under construction)
Limnos	1	2007	2047	1 (for recyclables)
Samos	1	2008	2023	2 (under construction)

Municipal solid waste generation rates. According to the Regional Waste Management Plan as well as estimates from local and regional authorities, in total, approximately 94,000 tons of waste is generated and subsequently landfilled throughout the region of North Aegean every year (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, personal communication, July 22, 2015; Region of North Aegean, 2015; Association of Local Authorities of Municipalities of Vathi and Pithagorio, 2014; Municipality of Chios, personal communication, July 23, 2015). It is important to note that the landfill in Samos accepts both municipal solid and construction and demolition waste, which increases the total amount of landfilled waste and the average disposal fee (Association of Local Authorities of Municipalities of Vathi and Pithagorio, 2014). As can be seen in Table 7, annual per capita waste generation in the region of North Aegean ranges from 417kg in Chios to 545 kg per person in Samos, with an average value of approximately

496 kg, which is higher than Europe's average of 481kg, but lower than Greece's average of 510 kg (Eurostat, 2015b).

Table 7. Municipal Solid Waste Generation in the Region of North Aegean.

Island	Population	Total Municipal Solid Waste Generation (tons)	Waste per Capita (tons)
Lesvos	86,436	46,000	0.532
Chios	52,674	22,000	0.417
Limnos	17,262	8,000	0.463
Samos	32,977	18,000	0.545
TOTAL	189,349	94,000	0.496

Local authorities weigh waste that goes through transfer and recycling stations, as well as landfills on a daily basis. Therefore, the estimates include the significant influence of tourism activity and seasonal residents. This is useful for this analysis, as most studies often rely on broad estimates and sensitivity analyses to incorporate the potential additional demand from seasonal populations. Figure 5 illustrates the influence of population dynamics, which is enough to magnify waste generation by at least 20% during spring and the summer months throughout the region. Specifically, during the summer months average municipal solid waste generation in Lesvos, Chios, Samos, and Limnos increases by approximately 50%, 30%, 49%, and 35%, respectively. The island with the most abrupt change is Lesvos, which is reasonable since it is the island with the highest number of visitors and second

homeowners in the region (Association of Greek Tourism Enterprises, 2015; Hellenic Statistical Authority, 2014).

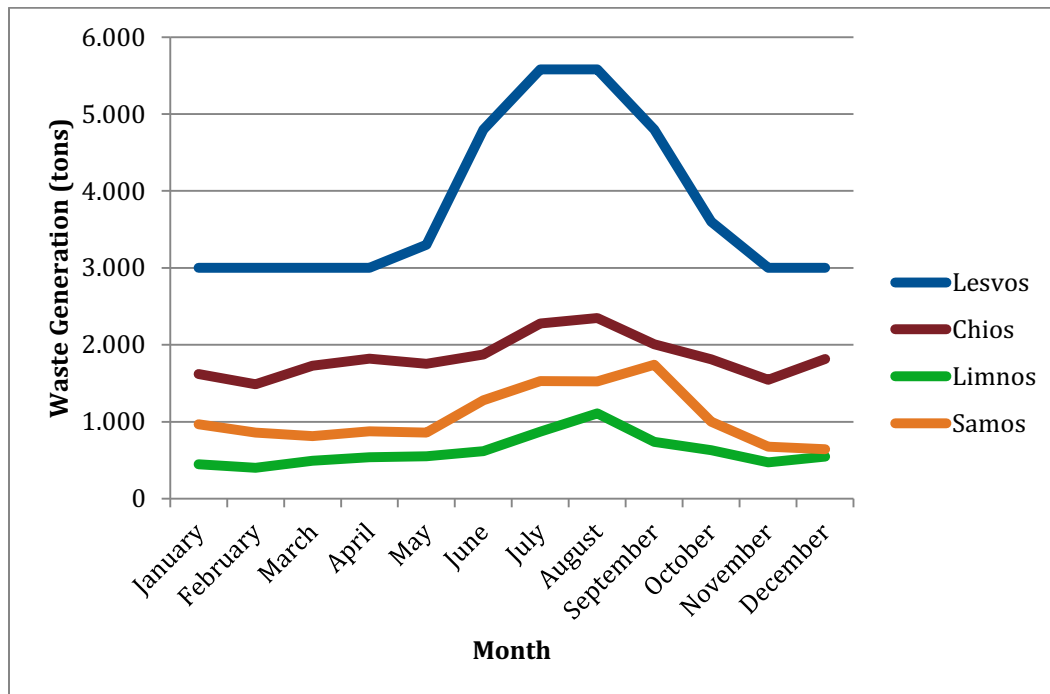


Figure 5. Seasonal variation in municipal solid waste generation.

Municipal solid waste composition. As illustrated in Table 8, according to the Regional Waste Management Plan, municipal solid waste in the region of North Aegean is characterized by a relatively high organic and paper content, followed by plastics, metal, glass, and wood (Region of North Aegean, 2015). These values, especially the organic content of waste, are typical for countries in the Mediterranean region, since they are heavily influenced by cultural habits and climatic conditions. Notably, the composition of waste is important in order to facilitate effective plans and calculate whether the assumed heating value and energy content of municipal solid waste would be high enough in order to produce viable amounts of energy.

Table 8. Composition of municipal solid waste in the region of North Aegean.

Material	% in Municipal Solid Waste
Organics	44.3
Paper	22.2
Plastics	13.9
Wood	4.6
Metals	3.9
Glass	4.3
Other	6.8

As shown in Table 9, in addition to municipal solid waste, because of the region's significant agricultural and industrial activity considerable amounts of agricultural, construction and demolition, and other industrial wastes are generated throughout the region. This adds considerable pressures on the current waste management system, since all of these wastes require specific disposal sites. The local authorities, however, so far have been unable to find designated waste disposal sites for non-municipal solid wastes (Region of North Aegean, 2015). As a result, construction and demolition waste open dumps are still found in marginalized areas and former industrial complexes, since most of the time, without an integrated management and transfer system, it is very expensive for individual waste generators to transfer and dispose of their own waste in landfills that are located at large distances.

Furthermore, when these wastes are disposed of in landfills, not only they introduce potential occupational and health hazards but also significantly reduce the estimated

operational lifetime of the disposal sites and increase operational costs. The region is also home to additional sources of waste, such as algae and seaweed, which are not found in mainland regions in such large amounts. These wastes are not regarded as municipal solid waste, however, they commonly end up in landfills along with agricultural waste residues.

Table 9. Non-municipal solid waste generation in the region of North Aegean.

Type	Quantity (tons /year)
Wastewater Sludge	23,812
Used Tires	540
End-of-life Vehicles	3,000
Construction & Demolition Waste	98,915
Electronic Waste	3,200
Agricultural Waste	58,000
Cheese Waste Residues	29,650
Wine Waste Residues	1,978
Livestock Waste Residues	80,057

Municipal solid waste management costs. Currently the region spends more than \$5 million annually in order to dispose of waste in landfills. Moreover, disposal costs are set to increase in the following years because the region plans to foster recycling and sustainable waste management action plans at the community level (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, personal communication, July 22, 2015). Disposal costs are exacerbated throughout the region by the presence of multiple and

dispersed small-scale facilities, which hinders the potential for favorable economies of scale. Specifically, recycling and waste management on the islands becomes increasingly expensive due to the relatively larger transport distances between the generation source and the disposal site, compared to mainland and other island regions, as well as the lack of comprehensive facilities that can drive processing and management efficiencies. Table 10 presents an overview of the municipal solid waste disposal costs in each island.

Table 10. Municipal solid waste disposal costs in the region of North Aegean.

Island	Landfill Disposal Cost	
	\$ million	\$/ton
Lesvos	2.25	48.913
Limnos	0.4	50
Chios	1.68	76.36
Samos	0.877	50

Primary data from local authorities reveal that the average disposal cost per ton of processed waste ranges from \$49 to \$179. This significant difference in disposal costs can be explained by analyzing the relative size of the island and the exact distance of the community from which waste is transferred to the local disposal site. Given that finding adequate sites for landfill developments has been extremely complicated throughout the region due to community opposition and land ownership issues, landfills have been sited far away from population centers, usually across mountainous areas. As such, transporting waste to these sites becomes increasingly difficult when communities are located far away from the disposal

site, which tends to increase prices. Multiple transfer stations are utilized in order to transport waste to landfills, which is enough to triple the total disposal costs for some specific communities. In Lesvos, for instance, communities that are located close to the disposal site pay \$49.3 per ton of landfilled waste, while communities that are located on the opposite part of the island pay up to \$86.2 per ton of landfilled waste (Intermunicipal Enterprise for Waste Management and Environmental Development of Lesvos, 2015).

Energy Generation in the Region of North Aegean

As illustrated in Figure 6, like most Greek island regions, the region of Northern Aegean depends substantially on imported fossil fuels for electricity generation and transportation (Hatziaargyriou et al. 2012; Region of North Aegean, 2014). Despite the significant potential to develop widespread renewable energy networks (Region of North Aegean, 2014), Lesvos, Chios, Limnos, and Samos are all non-interconnected energy systems, home to autonomous power stations running on imported diesel fuel. In 2013, Lesvos, Chios, Limnos, and Samos spent \$38, \$23.5, \$11.19, and \$21.3 million, respectively, to import petroleum products to satisfy their energy needs (Regulatory Authority for Energy, 2015). Notably, every citizen pays an equal fee through a tax called Service of General Interest in order to subsidize these imports (Regulatory Authority for Energy, 2015).

These autonomous systems are not only prone to a variety of malfunctions and interruptions during periods of abruptly high and variable demand (Region of North Aegean, 2014) that substantially increase the average electricity market price, such as the summer months, but also generate significant amounts of greenhouse gases that contribute to climate change (Hatziaargyriou et al., 2012).

According to Rokas Renewables (2012), the autonomous energy generation stations throughout the region of North Aegean emit approximately 0.62 tons of carbon dioxide per MWh of electricity, which places them among the most polluting energy sources in the country. Moreover, the system is remarkably vulnerable to oil price shocks, which exacerbates uncertainty and energy price vulnerability.

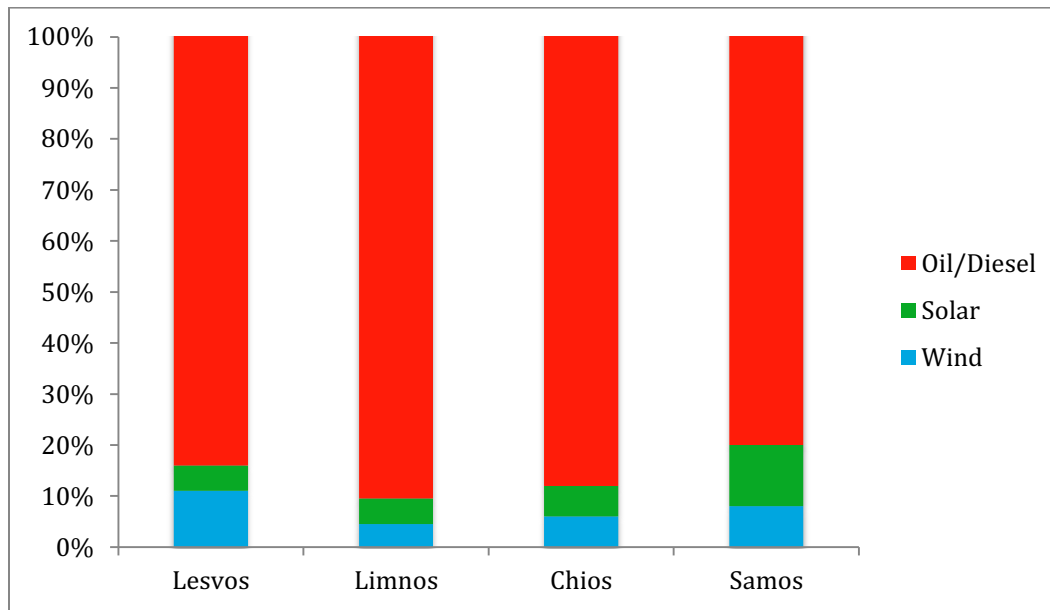


Figure 6. Electricity generation by energy source in the region of North Aegean.

As illustrated in Table 11, although the average demand for electricity is lower compared to mainland regions, the aforementioned challenges increase the average price of electricity to very high levels. In Limnos, for instance, the average price of electricity is four times more expensive compared to average prices in the interconnected system of mainland Greece (Regulatory Authority for Energy, 2015), while the price difference skyrockets during the periods of the highest demand.

Table 11. Electricity demand and generation costs.

Island	Electricity Needs (MWh)	Generation Cost (\$/MWh)	Generation Cost in Mainland (\$/MWh)	Island / Mainland Price
Lesvos	285,542	220.68	64.75	3.40
Chios	196,993	199.68	64.75	3.08
Limnos	58,486	272.09	64.75	4.20
Samos	136,178	249.21	64.75	3.85

Although the main islands in the North Aegean Sea are currently not connected with each other, a long-term plan for the development of an interconnected system has already been proposed and included in the most important strategic energy investments by the Hellenic Transmission System Operator (Regulatory Authority for Energy, 2015). This development would introduce additional prospects for synergistic links between the islands as well as the opportunity to spread additional benefits from the proposed solution towards the least developed islands.

The Proposed Waste-to-Energy Gasification System

The chosen technology for the waste-to-energy plant is advanced thermal gasification. Thermal gasification is a thermochemical process through which carbon-based materials, such as municipal solid waste and biomass, are transformed into a variety of forms of energy (Enerkem, 2012). The thermal gasification process consists of two main phases and the final product is a synthetic gas compound, which is primarily composed of hydrogen and carbon monoxide (Figure 7). Feedstock materials are not burned completely with high

volumes of air, and as such this treatment process does not produce high amounts of carbon dioxide (Enerkem, 2012). First municipal solid waste is reacted with small amounts of oxygen, or oxidized, and subsequently gasified in the plant's primary chamber (Enerkem, 2012; Energos, 2015b). The gas is then cleaned and utilized in order to produce power in the form of electricity or heat, or renewable liquid fuels, chemicals, fertilizers and hydrogen through additional thermochemical processes (Enerkem, 2012; Energos, 2015b).

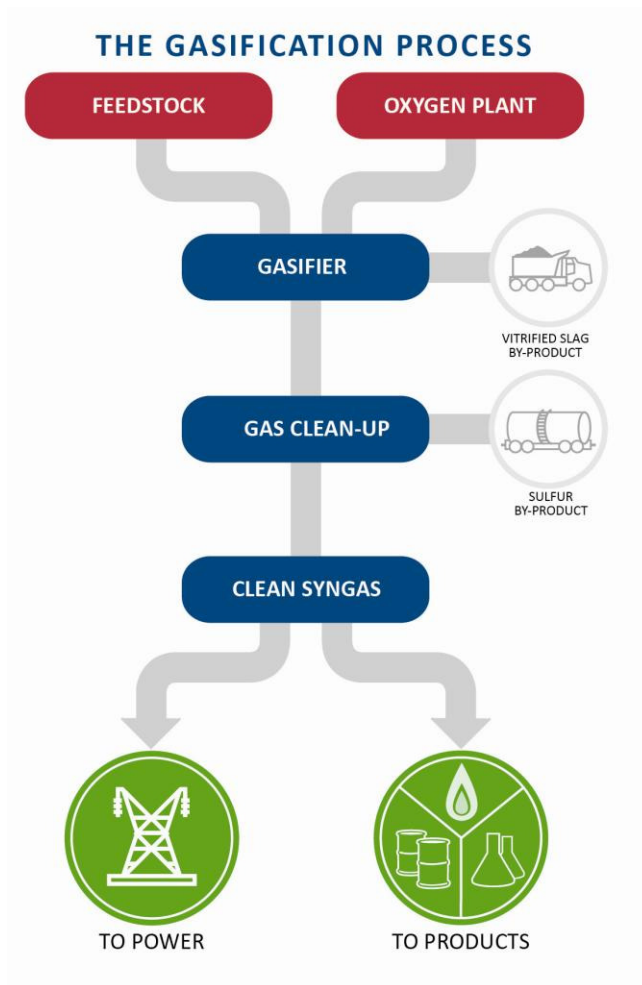


Figure 7. Schematic of the gasification process (Kerester, 2014).

Two different gasification plant designs are evaluated in this analysis. The first is similar to a typical ENERGOS gasification plant, and the second one similar to an Enerkem waste-to-biofuels gasification plant. ENERGOS is a gasification technology and power plant provider headquartered in Manchester, UK, with significant experience in designing and operating gasification power plants (ENERGOS, 2015b). ENERGOS power plants follow the conventional gasification process and convert solid wastes into renewable electricity and heat. The ENERGOS process converts waste into power, first by oxidizing and gasifying waste into a synthetic gas compound in a moving grate, and subsequently burning it in order to produce electricity and heat (ENERGOS, 2015b).

Enerkem is a waste-to-biofuels gasification technology and power plant provider headquartered in Montreal, Canada (Enerkem, 2015). Enerkem is among the first companies throughout the world to convert municipal solid waste into liquid fuels and chemicals (Lynch, 2015). Enerkem's process converts solid waste into syngas, which is then transformed into methanol and ethanol through additional thermochemical processes (Lynch, 2015). Methanol and ethanol can then be utilized for the production of renewable chemicals, such as acrylic acid, n-Propanol, and n-Butanol (Enerkem, 2015). According to Enerkem (2015), the company's proprietary process is cost-effective and environmentally sustainable, since it requires lower process temperatures and thus minimizes energy and maintenance costs (U.S. Department of Energy, 2010).

Figure 8 illustrates a typical Enerkem waste-to-biofuels plant. The most significant difference between conventional waste-to-energy gasification plants and an Enerkem waste-to-biofuels facility is the bio-refinery component, which converts syngas to renewable fuels (U.S. Department of Energy, 2010).

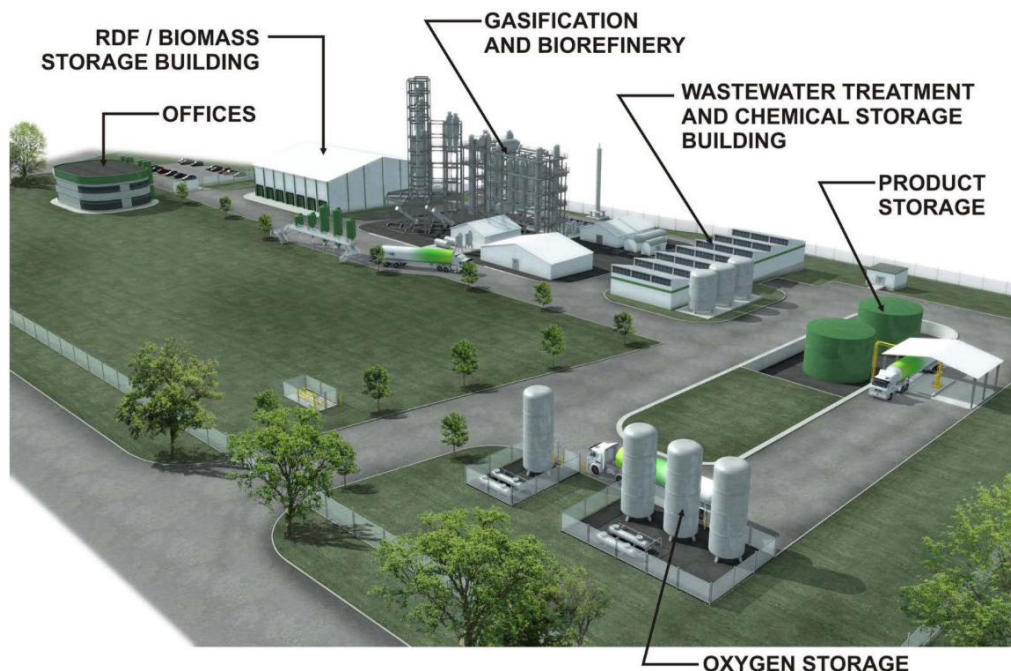


Figure 8. Schematic of a typical Enerkem waste-to-biofuels plant (Schubert, 2012).

Among the most significant benefits of the gasification technology is the potential to choose from a wide variety of output pathways and marketable products, since a typical power plant is able to produce synthetic gas, power, heat, as well as liquid fuels and chemicals (Figure 9). Liquid fuels and chemicals can also be transported to other regions that have higher market demand and prices, which allows plant operators to choose from additional potential sources of revenue. On the other hand, conventional waste incineration power plants produce electricity and heat, but are unable to produce chemicals or renewable fuels. Importantly, the production of liquid fuels also provides the flexibility to operate in batch process, which means that continuous operation is not as important as in conventional waste-to-energy plants, since having an adequate volume of feedstock is overall more significant (U.S. Department of Energy, 2010).

Furthermore, because of the differences in the conversion process, gasification plants usually produce higher amounts of energy and significantly lower amounts of carbon dioxide, and thus are more environmentally benign and efficient (U.S. Department of Energy, 2010).

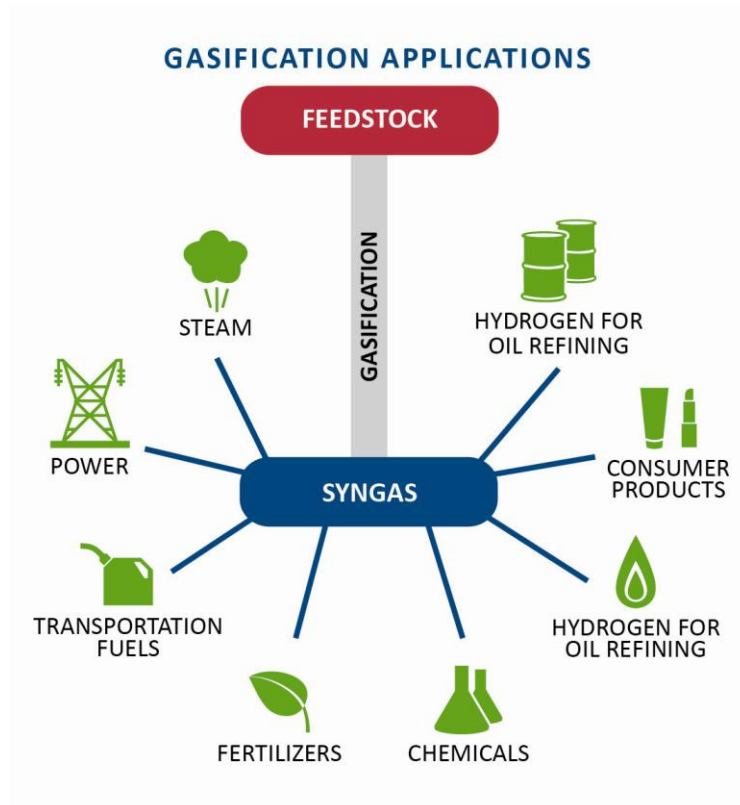


Figure 9. Gasification output pathways (Kerester, 2014).

The design of a typical plant is also more flexible compared to conventional waste-to-energy incineration plants, which means that in addition to municipal solid waste, gasification plants are able to accept a variety of wastes and products with a wide range of properties and energy content, such as non-hazardous industrial and agricultural wastes, without introducing operational uncertainties and jeopardizing the plants overall performance

(U.S. Department of Energy, 2010). This provides gasification plants with a variety of additional low-cost feedstock options and reduces processing, operational and logistics costs.

Furthermore, both ENERGOS and Enerkem have developed modular plant designs. As such, the plants are more compact and have a significantly lower footprint compared to conventional waste-to-energy plants, while additional modules can be added incrementally at a later time if additional capacity is needed, thereby eliminating the need for exceptionally large investments and the potential for redundant residual capacity. Most of the components are pre-fabricated and can be assembled and installed in a timely and efficient manner, further reducing construction costs and time requirements.

All of this makes gasification an ideal waste management solution for island environments.

Technical Design of the Plant

The facility is designed to accommodate all municipal solid waste management needs throughout the region of North Aegean. As such, it will be able to treat an annual amount of approximately 94,000 tons of municipal solid waste, as well as 26,000 tons of non-hazardous industrial and construction and demolition waste, and agricultural and forest residues. The second waste stream (non-municipal solid waste) would also be used on a make-up basis when and if required to cover any additional residual needs. Waste transport and treatment contracts would be re-examined annually in order to evaluate and specify the need for any necessary additions, such as changes in municipal solid waste composition, waste generation rates or recycling mandates and needs, for the whole duration of the project.

Feedstock Pre-Treatment

Currently, the waste transfer station network that exists throughout the region is able to pre-treat (remove non-convertible materials) and transport all waste to the proposed facility. However, a designated feedstock pre-treatment building would be provided in the immediate vicinity of the facility to offer additional storage as well as pre-treatment works when and if required.

Site Location

The site of the proposed facility is located in Lesvos, since it is the largest island throughout the region and the center of economic activity, which consequently means that it is close to the largest amounts of waste generation and energy needs. Furthermore, Lesvos' only diesel-fueled electric power plant, owned by the Public Power Corporation, is located right on the outskirts of the capital city of Mytilene, which provides significant symbiotic opportunities for heat and by-product utilization.

The chosen site is strategically located on marginalized land, and has excellent connections to the road system and all necessary utilities. Both Lesvos' sanitary landfill and Mytilene's transfer station, as well as the population centers with the largest waste generation rates are located at a close distance, which simplifies logistics planning and minimizes operational costs. Other than the electric power plant, the immediate surroundings consist of abandoned warehouses and industrial buildings from former industrial complexes, though some factories and industrial establishments are still active in the area. Moreover, the site is located approximately 400 meters away from a densely populated residential area, making the utilization of heat for citywide district heating purposes a technically and economically

feasible option. Furthermore, the site could be used as a starting point for the development of a wider eco-industrial park, which would benefit from cheap energy and heat, as well as additional waste and by-product exchanges.

Transportation of Waste

The location of the proposed development is in Lesvos, and as such, waste has to be transported there from the other islands and across Lesvos. The existing network of transfer stations and waste collection and transfer trucks will be utilized for the transportation of waste to the ports of Chios, Limnos, and Samos. Then, ships will be used to transport waste to the port of Lesvos. Ships are already used to transport waste in the region, usually from smaller islands without sustainable disposal means to larger islands with more developed networks, such as Aghios Efstratios, which transports its waste to Lesvos.

In Lesvos, the existing network of transfer stations and waste collection and transfer trucks will be used to transport waste from across the island, as well as the incoming waste streams from the other islands, to the location of the proposed facility, which is located approximately 2 km away from the port of Mytilene.

Plant Configuration

A typical gasification plant includes the following principal components: a gasifier, waste bunker, storage buildings, feedstock preparation chamber, oxidation chamber and the administration buildings (ENERGOS, 2015a). In total, the building area requirement is approximately 3,800 m², while the total site requirements are approximately 14,000 m² (ENERGOS, 2015a). Because of the difference in technologies and output pathways,

Enerkem's design requires additional buildings and components, which increases the total office building area. As presented in Table 12, overall, the two designs have similar site area requirements.

Table 12. Typical components of Enerkem and ENERGOS facilities.

Component	Size (m²)	
	ENERGOS	Enerkem
Site Area	14,000	18,000
Office building	3,800	557
Gasification island		725
Feedstock storage building		1338
Oxygen storage area		1560
Waste water building		557
Methanol production island	-	300
Ethanol production island	-	300
Methanol compressor shed	-	75

Cost-Benefit Analysis

The Business-as-Usual System

Capital costs. The total capital cost requirements for the duration of the analysis in the case of the existing waste management system are estimated at \$115.09 million. This includes operational and maintenance costs for the existing landfills, as well as total investment costs for the construction of identical landfills after the useful operational lifetime of the existing

ones expires and closure, subsequent revitalization and post-closure maintenance costs.

Closure and reclamation costs usually include the installation of a final cover and cap and a landfill gas collection system, while post-closure maintenance costs include designated programs to ensure that the final cover installation is working appropriately, leachate collection works and groundwater and methane gas monitoring installations (Government Gazette of the Hellenic Republic, 2003; U.S. Environmental Protection Agency, 2014). Post-closure maintenance periods are usually 30 years after closure, which is the period assumed in this analysis.

Lesvos, Chios, Limnos and Samos spent \$11.16 M, \$10 M, \$5.58 M, and \$5.58 M for the construction of their landfills, respectively. As such, it is estimated that a similar amount will be required for the construction of identical landfills once the capacity of the existing ones is reached. As presented in Table 13, over the duration of the analysis, Lesvos, Chios, Samos, and Limnos would need to construct two, two, three, and one landfill facilities, respectively. The analysis does not consider any potential additional investment requirements due to land acquisition and purchases, and considers that all necessary land will be readily available to be acquired for a landfill site.

Operation and maintenance costs. The operational and maintenance costs are estimated at approximately \$5.2 million per year (Table 13). This includes estimates for wages, utility costs, transportation costs, as well as operational and management costs for all four operational landfills throughout the region of North Aegean. According to the local authorities, waste disposal costs account for more than 50% of overall municipal solid waste management costs, since the transfer station network has considerably enhanced the efficiency of the solid waste collection system.

Table 13. Municipal solid waste management costs in the business-as-usual case.

Island	Financial Cost		Number of New Facilities Required over Analysis
	O&M	Capital	
Lesvos	\$2.25 M	\$47.8 M	2 landfills
Chios	\$1.68 M	\$29 M	2 landfills
Limnos	\$0.4 M	\$9.5 M	1 landfill
Samos	\$0.877 M	\$28.56 M	3 landfills

Revenue estimates. Other than the gate fee that municipalities pay in order to dispose of solid wastes in landfills, currently there is no other source of revenue for municipal landfill sites.

The potential for enhancements and modifications in order to develop a landfill gas-to-energy application to produce electricity or recycling systems to utilize recovered materials, now or in the future, and the consequent additional revenue streams, were not investigated in this analysis.

The Proposed Waste-to-Energy Gasification System

Capital costs. The total capital cost for the construction of the proposed gasification facility is estimated at approximately \$80 million (Table 14). This estimate was derived by analyzing the total investment costs of ENERGOS and Enerkem facilities of a comparable capacity throughout the world. The costs include estimates for construction, engineering, and pre-treatment works.

Table 14. Total investment capital needs for each evaluated scenario.

Scenario	Investment	Comments
Business as Usual	\$115.09 M	<ul style="list-style-type: none"> • Land acquisition • Buildings • Equipment • Replacement costs
ENERGOS Gasification	\$80 M	
Enerkem Gasification	\$80 M	

Operation and maintenance costs. Operation and maintenance costs were estimated by analyzing the total requirements of ENERGOS and Enerkem facilities of a comparable scale and output throughout the world. The operation and maintenance costs of such facilities are usually divided into variable and fixed costs. Variable costs include electricity, chemicals, consumables, and waste disposal and water treatment costs. Other than maintenance costs, fixed costs include testing, and environmental, administrative and facility personnel.

As such, approximately \$8 million would be required to run a gasification facility with the capacity to treat 120,000 tons of waste annually. In this case, gate fees and transportation costs are partly subsidized by the local municipalities, since \$31.35 and \$17.65 per ton of waste would be paid by local communities in order to transport and dispose of waste at the proposed facilities. The estimates include wages for a staff of approximately 50 employees. Overall, the operation and maintenance costs account for approximately 5 to 10% of total capital costs.

Most of the facility assets are expected to be operational for at least 30 years without requiring any major replacements. Furthermore, preventative maintenance programs include annual maintenance initiatives of approximately 22 to 26 days, as well as major overhauls

every 7 to 10 years (Enerkem, 2012). As such, the facility is expected to be operational for at least 8,000 hours, or 333 days, every year (Enerkem, 2012).

Revenue estimates. The proposed ENERGOS gasification facility will be able to produce 0.65 MWh of electricity per ton of waste processed, while the proposed Enerkem waste-to-biofuels facility will be able to produce 0.133 MWh of electricity per ton of waste processed. These estimates were derived by analyzing the efficiency and energy production capacity of similar ENERGOS and Enerkem facilities, and include both electricity lost through parasitic loads as well as energy loads for the thermal and thermochemical processes.

According to the Regulatory Authority for Energy (2015), Greece has enacted several feed-in tariff schemes to support renewable energy developments. In particular, the focus has been on supporting the timely achievement of the 20% renewable energy generation goal, which is enacted at the European Level. As such, according to Law 4254/2014, energy generation through gasification of biomass and wastes is subsidized through 25-year Power Purchasing Agreements at approximately \$166.8 – 191.5 per MWh, depending on the exact power output (Government Gazette of the Hellenic Republic, 2014). Electricity generation in stations with installed capacity greater than 5 MW is subsidized at \$166.8 per MWh, while electricity generation in stations with installed capacity less than 5 MWh is subsidized at \$191.5 per MWh. The ENERGOS gasification plant capacity falls within the lower end of the subsidy range, and as such electricity generation is subsidized at \$166.8 per MWh, while the Enerkem waste-to-biofuels plant falls within the higher end of the subsidy range and electricity generation is subsidized at \$191.5 per MWh.

Excess heat produced through the gasification process would be utilized within the facility to cover energy and heating needs, as well as to provide heat to adjacent industrial

and residential establishments, such as the Public Power Corporation diesel-powered power plant. Such heating agreements are subsidized through 25-year Power Purchasing Agreements at \$50.7 per MWh (Margaritis, Rakopoulos, Mylona, & Grammelis, 2014).

The proposed ENERGOS facility will be able to produce approximately 1.8 MWh of heat per ton of waste processed, while the Enerkem waste-to-biofuels facility will be able to produce approximately 0.2 MWh of heat per ton of waste processed. These estimate were derived by analyzing plants with similar treatment capacities and output, and include parasitic loads as well as energy needs for the thermal and thermochemical processes.

A typical 10 million gallon per year Enerkem facility is able to process waste and produce methanol, ethanol, or both. Operators have the option to restrict production to methanol, in which case the facility is able to produce 550 liters of methanol per ton of municipal solid waste (Chornet, 2012). As such, since the total input of the proposed facility is 120,000 tones of municipal solid waste, up to 66 million liters of methanol, or approximately 17.5 million gallons, would be produced annually. ENERGOS facilities currently restrict production to electricity and heat and do not produce fuels or chemicals.

The average market price of methanol in 2015 was used in this analysis. According to Methanex (2015), methanol prices in Europe averaged at \$1.34 per gallon in 2015, which leads to an annual revenue stream of approximately \$ 23.71 million. When the desired final product of the Enerkem facility is ethanol, a typical facility is able to produce 380 liters of ethanol per metric ton of municipal solid waste (Lynch, 2015). As such, up to 45.6 million liters of ethanol, or 10 million gallons, would be produced annually.

The average market price of ethanol in Europe for 2015 was used in this analysis. According to market reports, European ethanol price averaged at \$2.40 per gallon in 2015

(CME, 2015), which leads to an annual revenue stream of approximately \$24.30 million. An Enerkem facility could also utilize methanol and ethanol in order to produce a variety of different chemicals and additives (Lynch, 2015). However, this option was not investigated in this analysis. Notably, Enerkem emphasizes that chemical production is estimated to be a significant source of revenue for a typical facility, given the variety of different potential outputs as well as their high market value and demand (Lynch, 2015).

Energy recovery from municipal solid waste decreases carbon emissions and thus allows treatment facilities to qualify for carbon emission exceptions under the European Union's Emissions Trading System (European Commission, 2013). Since in the business as usual scenario municipal solid waste is disposed of in landfills, which do not recover landfill gas for electricity generation, one ton of carbon dioxide would be avoided for every ton of municipal solid waste that is processed in a gasification facility (Themelis & Mussche, 2014). Moreover, in the case where syngas is utilized to produce renewable fuels and chemicals, up to three tons of carbon dioxide would be avoided per every ton of municipal solid waste (Lynch, 2015). Currently, the average carbon price under the Trading Scheme in Greece is \$8.38 per ton of CO₂ (Operator of Electricity Market in Greece, 2015). Therefore, the proposed facility would receive an additional income stream of \$8.38 per ton of municipal solid waste when waste is utilized to produce energy, and up to \$25.14 per ton of municipal solid waste when waste is utilized to produce renewable fuels and chemicals.

Financial Assessment

Three different scenarios were evaluated and the full range of benefits and costs over the 50-year analysis period with a discount rate of 10% is presented in Table 15. The

business as usual scenario represents the current waste management system in the region of North Aegean. The ENERGOS gasification scenario represents a scenario in which waste is managed through an ENERGOS gasification plant, and the Enerkem gasification scenario represents a scenario in which waste is managed through an Enerkem waste-to-biofuels plant.

Table 15. Cost-benefit analysis performance summary.

Financial Lifecycle Summary	Business as Usual		ENERGOS Gasification		Enerkem Gasification	
	Total	Total PV	Total	Total PV	Total	Total PV
Capital Costs	-\$115.09 M	-\$77.23 M	-\$80 M	-\$73 M	- \$80 M	-\$73 M
O &M Costs	-\$610.16 M	-\$71.78 M	-\$902.4 M	-\$110 M	- \$902 M	-\$110 M
Electricity Sales	-	-	\$1.467 B	\$179 M	\$349.7 M	\$43 M
Heat Sales	-	-	\$1.235 B	\$151 M	\$141 M	\$17 M
Carbon Credits	-	-	\$113.4 M	\$14 M	\$340.1 M	\$41 M
Biofuels Sales	-	-	-	-	\$2.786 B	\$340 M
TOTAL	-\$737.9 M	-\$151.2 M	\$1.834 B	\$161 M	\$2.635 B	\$258 M

Both proposed solutions result in significant economic benefits over the course of the evaluated period. In the case of the ENERGOS gasification scenario, electricity and heat sales represent the largest sources of revenue, accounting for almost 96% of total revenues, while in the case of the Enerkem gasification scenario biofuel sales represent the largest source of revenue with 77% of total revenues. In the absence of technological modifications to utilize landfill gas and produce electricity or recycle materials, the business as usual

system currently does not have any additional source of revenue, other than the municipal landfill gate fees. Carbon credits further enhance the profitability of the proposed alternative scenarios by adding revenue streams of approximately \$113 million, and \$340 million in the ENERGOS and Enerkem scenarios, respectively.

The results of the financial analysis are presented in Table 16. The resulting internal rate of return for both alternative scenarios is greater than 30%, while the respective breakeven point periods are less than 5 years, making them considerably feasible from an investment point of view. On the other hand, the business as usual scenario does not result in any economic benefits, and consequently has a negative cost-benefit ratio. The Enerkem gasification scenario is the most economically feasible scenario with a cost-benefit ratio of 2.41 and a payback period of approximately 3 years. The highly efficient production of biofuels, along with some electricity, heat and by-product production, renders it the most feasible alternative. However, the ENERGOS gasification scenario is also economically attractive compared to the business-as-usual system.

Table 16. Financial performance evaluation.

Scenario	IRR (%)	Breakeven Point (years)	Benefit-Cost Ratio
Business-as-Usual	-	-	-
ENERGOS Gasification	30.723	4.5	1.88
Enerkem Gasification	47.31	3	2.41
Enerkem Gasification: Methanol only	44	4	2.33

Environmental Assessment

In addition to the financial analysis, several environmental parameters were also evaluated and the results are presented in Table 17. In addition to the greenhouse gas emissions savings from reduced landfill disposal, emissions savings are also gained from generating renewable electricity through the thermochemical processes, since approximately 0.62 tons of carbon dioxide would be avoided per every MWh generated through waste gasification. In total, approximately 89,000 and 46,800 tons of CO₂ emissions savings are gained in the ENERGOS and Enerkem cases, respectively. As such, the proposed development would reduce greenhouse gas emissions annually by 135,800 tons of carbon dioxide in the case of an ENERGOS gasification facility, and by 277,000 tons of carbon dioxide in the case of an Enerkem waste-to-biofuels gasification facility. According to the U.S. Environmental Protection Agency (2015), this is the equivalent of removing approximately 60,000 passenger vehicles off the road in the Enerkem case, and approximately 30,000 passenger vehicles in the ENERGOS case.

The elimination of landfilling practices throughout the region of North Aegean would result in substantial savings. Avoiding the need to construct, maintain, close, and revitalize new landfills results in capital savings of more than \$115 million over the duration of the analysis. Moreover, according to expert evaluations, 1 m² is lost for every 10 tons of municipal solid waste that is disposed of in landfills (Themelis & Mussche, 2014). As such, approximately 150 acres of land would be conserved over the duration of the analysis if waste were to be treated through gasification instead of landfilled. The thermochemical gasification process also results in the production of char and inert residuals, which will be utilized as aggregate for construction materials, and water, which would cover water needs

for agricultural and landscaping purposes, providing additional opportunities for natural resource savings.

Additionally, avoiding the disposal of waste in landfills also minimizes leachate generation. Approximately 0.3 m³ of leachate is produced per every ton of solid waste (Santucci, Puhl, Sinha, Enayetullah, & Agyemang-Bonsu, 2015), which means that the proposed development would minimize the need to manage and treat approximately 2 million cubic meters of leachate over the duration of the analysis. Modern landfill designs include comprehensive technical modifications to manage and treat leachate, however, despite the sophistication of the management techniques leachate leaks are due to happen, which introduce significant threats to natural environments, especially surface water bodies.

Table 17. Environmental performance evaluation.

Scenario	GHG Emissions Reduction (tCO ₂)		Reduced Landfill Disposal		Resource Recovery		
	Landfill (tCO ₂)	Electricity (tCO ₂)	Capital (\$ M)	Leachate (m ³)	Land (acres)	Slag (tons)	Water (gallons)
ENERGOS Gasification	89,000	46,800	115.09	1.8 M	148.3	18,000	4,640
Energkem Gasification	267,000	10,000	115.09	1.8 M	148.3	18,000	12 M

Results over 50-year analysis period with a 10% discount rate.

Social Assessment

The social assessment evaluated the benefits for the region and residents that are not captured by the financial and environmental assessments and the results over the 50-year analysis period with a discount rate of 10% are presented in Table 18. First among these is the potential impact on jobs. Both developments would result in the creation of a significant amount of new jobs during the construction and operation stages of the proposed development. In the case of the Enerkem waste-to-biofuels, 50 full time jobs would be created for the operation of the plant, while more than 200 jobs would be created for the construction of the facility as well as for the production of various components and materials. In the case of the ENERGOS gasification facility, approximately 30 full time jobs would be created for the operation of the plant, while more than 50 jobs would be created for the construction of the facility.

Furthermore, eliminating landfilling practices does not only result in the aforementioned economic and environmental benefits, but also significantly enhances the quality of life of the people as well as the state of the natural environments. Other than releasing significant amounts of greenhouse gases that contribute to climate change, landfills influence the health and average life expectancy of workers and the communities, as well as introduce risks that could impact the local natural environment (Santucci et al., 2015). It is important to note that when quantified, these additional impacts, especially impacts on human health, could considerably increase the average waste management cost (Santucci et al., 2015). However, these were not incorporated in this analysis.

The proposed development would also reduce the need for imports of petroleum products. According to expert evaluations, every ton of processed waste produces electricity

equivalent to one barrel of oil (Themelis & Mussche, 2014). As such, imports would be reduced by approximately 150,000 barrels of oil per year in the ENERGOS scenario. In the Enerkem scenario, approximately 7.1 million gallons of gasoline, or 374,000 barrels of oil, would be displaced through ethanol production, in addition to 25,000 barrels of oil through waste gasification. Consequently, imports would be reduced by approximately 400,000 barrels of oil per year. Through this reduction, over the duration of the analysis, the region would save approximately \$1 billion, or \$76 million in net present value, in the ENERGOS scenario, and over \$3.2 billion, or \$253 million in net present value, in the Eerkem scenario. Furthermore, it is important to note that although oil prices have fallen considerably during the first half of 2015, if prices were to increase in the near future, the profitability of the proposed development would also increase significantly. However, this scenario was not investigated in this analysis.

The project also qualifies for the benefits of Law 3851/2010, which specifies three additional revenue sources for the regions in which sustainable development projects are being developed (Ministry of Environment, Energy and Climate Change, 2010). First, 1.7% of the net annual income from renewable energy sales goes to the regional municipalities, then 1% goes directly to the local citizens through tax exemptions, while 0.3% goes to a designated Green Fund that is used to fund sustainable development projects and regulatory and environmental plans throughout Greece (Ministry of Environment, Energy and Climate Change, 2010). In total, over the 50 years of the analysis municipalities would receive approximately \$81 million in the ENERGOS gasification scenario and approximately \$15 million in the case of the Enerkem gasification scenario. Each citizen would receive approximately \$229,000 in the ENERGOS gasification scenario, and \$42,000 in the Enerkem

scenario. Last but not least, \$8 million would be reserved for the Green Fund to foster sustainable projects in the ENERGOS case and \$1.5 million in the Enerkem case.

Table 18. Social performance evaluation.

Scenario	Jobs	Reduced Oil		Regional Development (\$ M)					
		Imports (\$ M)		Region		Citizens		Green Fund	
		Total	NPV	Total	NPV	Total	NPV	Total	NPV
ENERGOS Gasification	80	609.10	74	46	6	27	3	8.11	1
Enerkem Gasification	250	2,030	248	8.19	1	4.91	1	1.47	0.2

Results over 50-year analysis period with a 10% discount rate.

Figures 10 and 11 illustrate the overall economic benefits over the 50-year analysis period with a discount rate of 10% when these additional revenue streams are incorporated into the financial analysis. The environmental and social benefits are enough to enhance the economic feasibility of the Enerkem scenario from \$258 million to \$583 million in net present value. Similarly, the economic profitability of the ENERGOS scenario is enhanced from \$161 million to \$322 million in net present value. In total, the region of North Aegean would gain more than \$690 million in the ENERGOS case and \$2 billion in the Enerkem case over the duration of the analysis. It is important to note that some of these revenues would increase significantly under certain scenarios, especially under different discount rates. However, these were not investigated in this analysis.

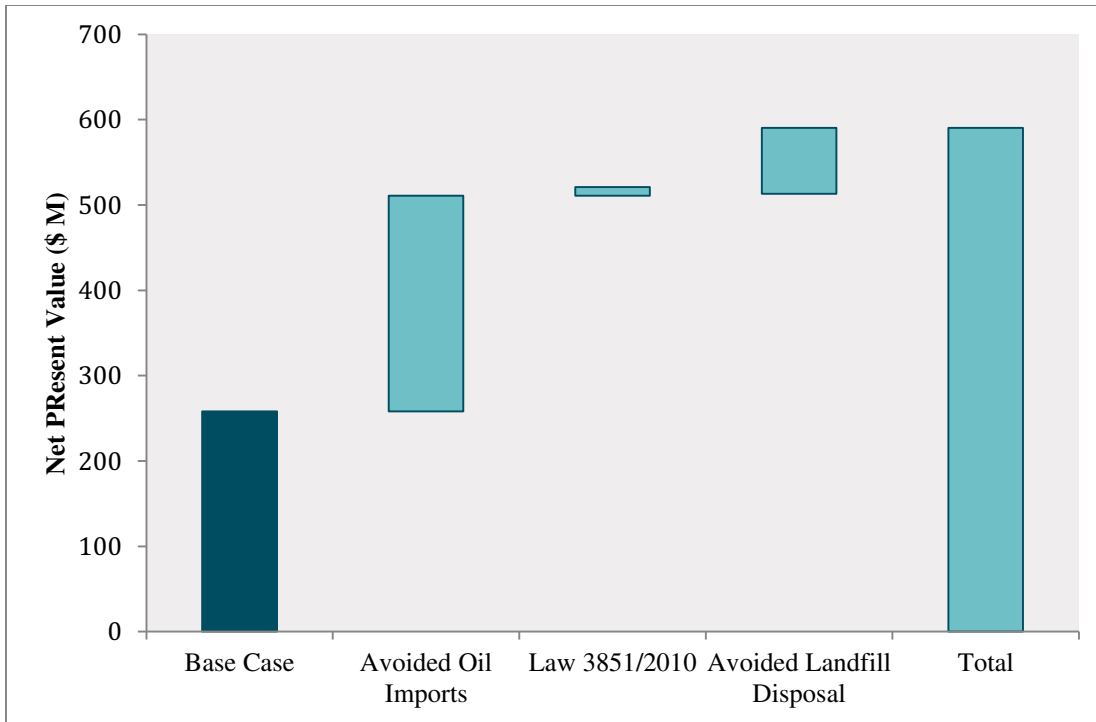


Figure 10. Total benefits for the region of North Aegean – Enerkem case.

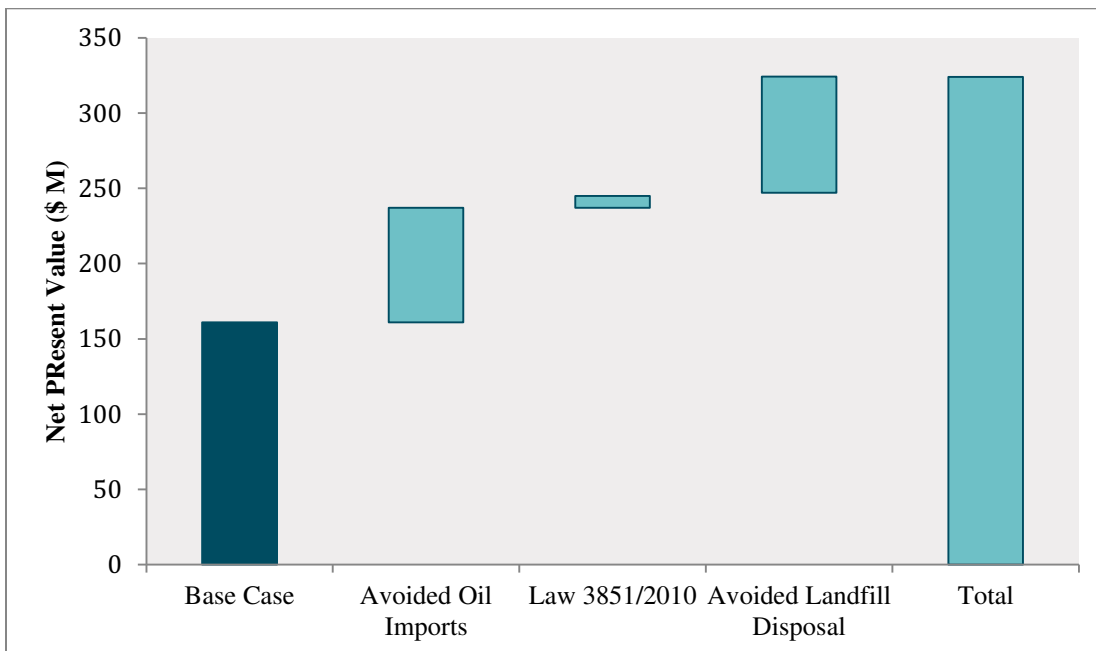


Figure 11. Total benefits for the region of North Aegean – ENERGOS case.

Sensitivity Analysis

Sensitivity analyses were performed for all three scenarios, and the results are illustrated in the following figures. First, the potential effect of a different discount rate was evaluated. Given the turbulent economic condition in Greece, a relatively high discount rate was used for the base analysis, however, sensitivity analyses allow for the investigation of different possible scenarios in case the financial climate changes for the better or for the worse in the near future. As such, several discount rates were evaluated, ranging from 2 to 16 %. As illustrated in Figure 12, with lower discount rates the economic feasibility of the proposed development and the unsustainability of the existing system increase exponentially. On the other hand, higher discount rates minimize the adverse effects of the need to continuously maintain and construct landfills and utilize fossil fuels through highly polluting means in the business as usual scenario.

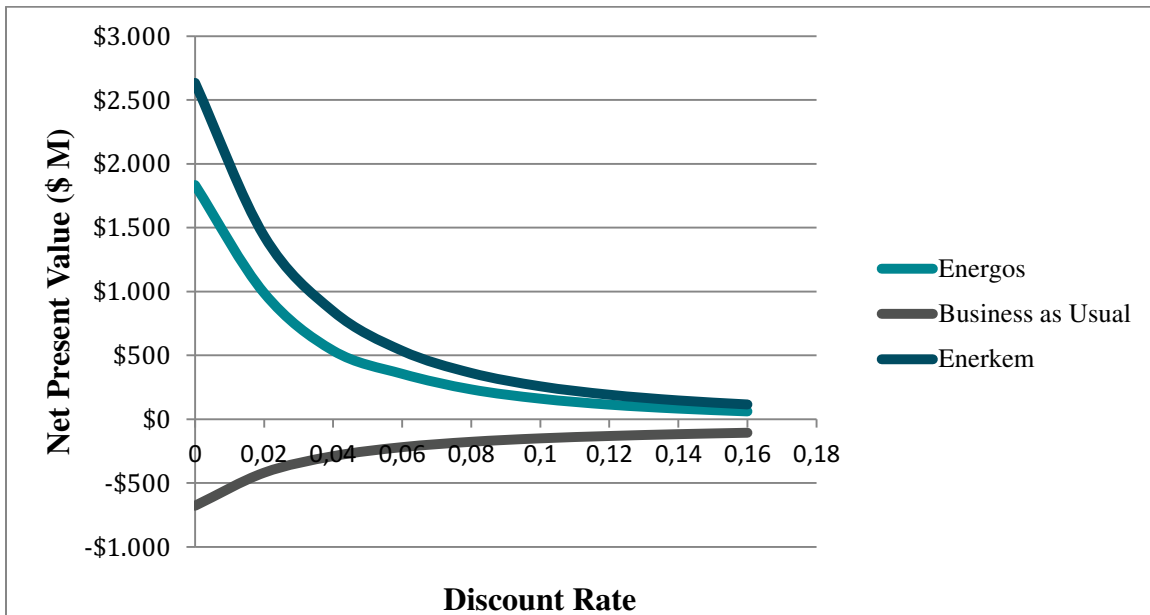


Figure 12. Discount rate versus net present value comparison.

The next parameter evaluated is the upcoming landfill tax. According to Laws 4042/2012 and 4257/2014, Greece is expected to introduce an incremental landfill tax by the end of 2015, starting from \$39.7 per ton of landfilled municipal solid waste, which would increase by \$5.7 every year until it reaches \$68 per ton of disposed solid waste (Government Gazette of the Hellenic Republic, 2012; 2014). However, since the landfill tax has not yet been introduced, several scenarios were evaluated in addition to the one anticipated by Law 4042/2012. Landfill tax values range from \$30 to \$60 per ton of landfilled municipal solid waste. As can be seen in Figure 13, although the introduction of a landfill tax does not enhance the profitability of the gasification scenarios, it does influence the economic feasibility of the business as usual scenario quite significantly. A \$30 landfill tax increases the total net present costs by 16% from \$151 million to \$175 million, while the anticipated landfill tax scenario increases the total net present costs by 48% to \$223 million.

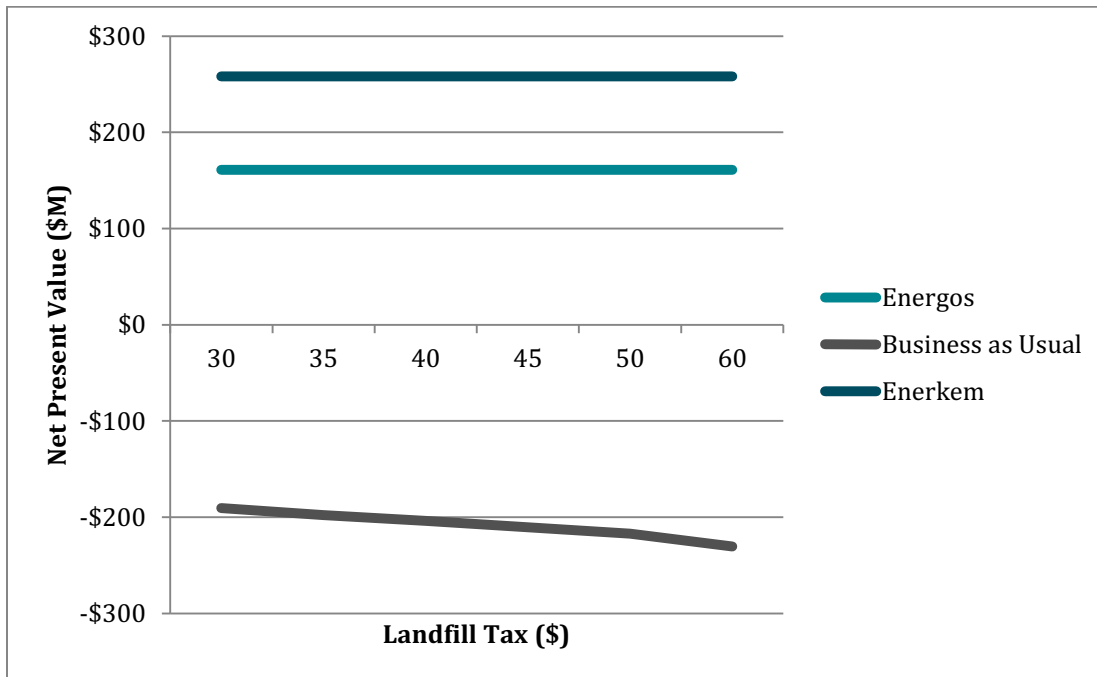


Figure 13. Landfill tax versus net present value comparison.

The introduction of a potential tax on carbon emissions at the European level was also evaluated. The European Union has been consistently discussing the potential of a carbon tax, and by some estimates is expected to introduce it within the next five years. As such, several carbon prices were evaluated, ranging from \$5 to \$100 per ton of CO₂, which were incorporated in the financial model from financial year 2018 and on. As illustrated in Figure 14, although a carbon tax would not directly influence the profitability of the gasification scenarios, it would significantly influence the financial sustainability of the business as usual scenario, since the existing system produces significant amounts of greenhouse gas emissions. Specifically, a \$30 tax on carbon emissions would increase the total net present costs by 24.5% from \$151 million to \$188 million.

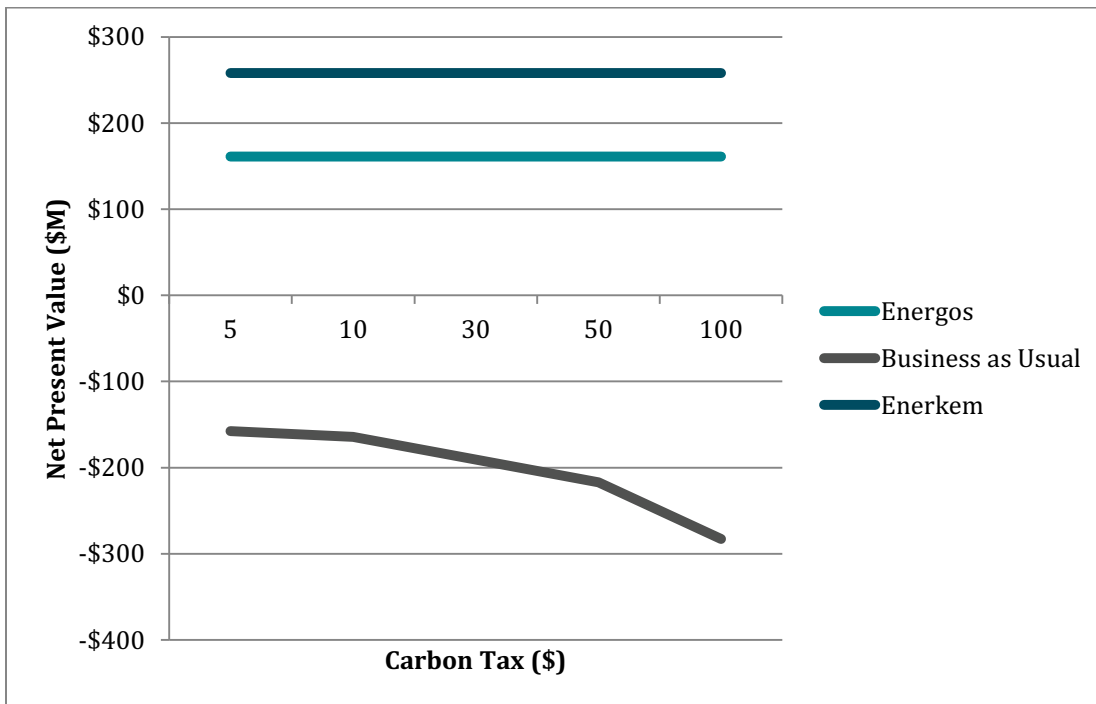


Figure 14. Carbon tax versus net present value comparison.

Moreover, because the landfill tax is going to be introduced by the end of 2015 and a tax on carbon emissions is likely to be introduced within the next years at the European level, the combined effect of the two parameters was also evaluated. Carbon tax prices range from \$5 to \$100 per ton of CO₂ and landfill tax prices range from \$30 to \$60 per ton of waste. As can be seen in Figure 15, the introduction of both policies indirectly enhances the economic feasibility of the proposed gasification facility. Although the revenue streams of the gasification scenarios remain the same, the costs of disposal and energy generation in the case of the existing waste management and energy systems increase to very high levels. The implementation of both the anticipated landfill tax scenario and a \$30 tax on carbon would increase the total net present costs by 73.5% from \$151 million to \$262 million.

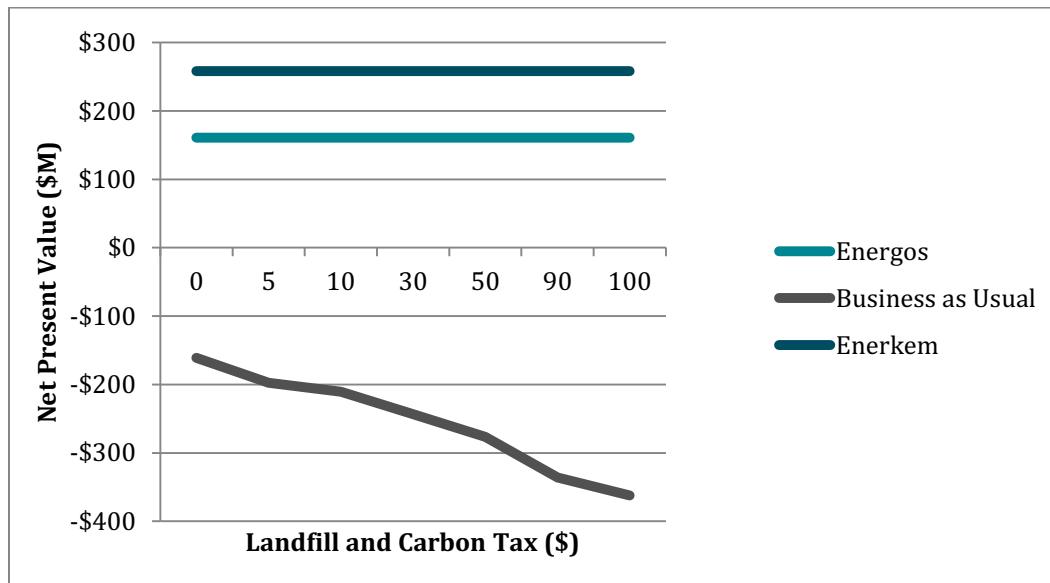


Figure 15. Landfill and carbon tax versus net present value comparison.

Notably, the combined effect of a landfill tax and a tax on carbon emissions has been influential in fostering a shift towards more sustainable waste management and energy

practices in countries that have managed to implement both instruments, such as Sweden (Swedish Waste Management, 2014).

Given that biofuels represent the largest source of revenue in the Enerkem gasification scenario, the potential impact of lower or higher biofuel market prices was also evaluated. As it can be seen, the average price of ethanol significantly affects the profitability of the Enerkem facility (Figure 15). Even if average ethanol prices drop by 60% to \$1 per gallon, the Enerkem scenario would still be economically feasible. The average price of ethanol has to fall by 32% to \$1.70 per gallon in order for the ENERGOS gasification scenario to be equally profitable. Notably, in this case the Enerkem scenario would result in an internal rate of return of 25% and a payback period of approximately 5 years.

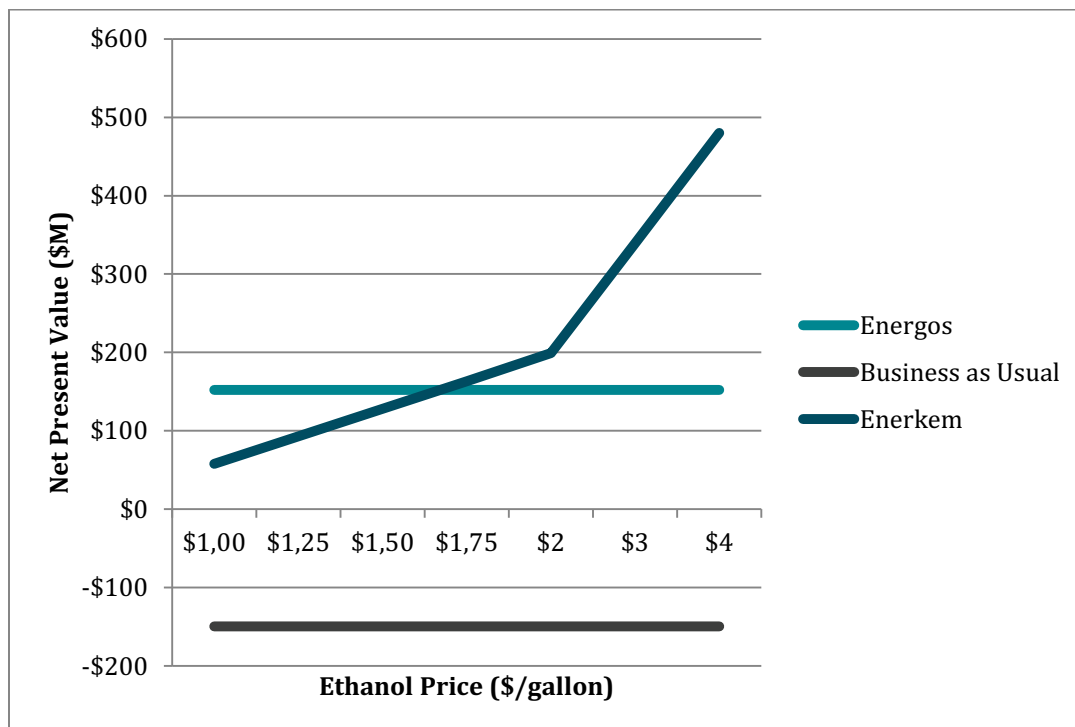


Figure 16. Ethanol price versus net present value comparison.

Chapter IV

Discussion

Assessing the economic, social, and environmental benefits and costs of the proposed solution and the business-as-usual system in the region of North Aegean revealed that the proposed development would be a more environmentally, socially, and economically feasible alternative for waste management and energy generation. Several synergies would be fostered with a wide range of sectors of the regional economy, while produced by-products would help conserve considerable amounts of valuable land, natural resources, and water. As such, the cost-benefit analysis supports and confirms the hypothesis that a novel mini grid based on a waste-to-energy facility will help satisfy the waste management, energy generation and water needs of a group of remote islands in the northern Aegean Sea in a more sustainable manner compared to the business-as-usual approaches.

Comparing the economic feasibility of the two systems revealed the importance of economies of scale regarding waste management and planning for synergies at the regional scale. Results showed that in the case of the existing system the costs far outweigh the benefits over the duration of the analysis, which led to a negative financial performance evaluation. On the other hand, from a financial perspective, the proposed development would lead to significant benefits, the net present value of which in most cases exceed the business as usual scenario by more than five times. Despite the relatively high discount rate, the investment yields more than two times the initial capital in net present value for both evaluated scenarios. Overall, over the duration of the analysis, the proposed development

would lead to benefits of approximately \$3.5 billion, or more than \$400 million in net present value in the Enerkem case and \$2.5 billion, or \$300 in net present value in the ENERGOS case.

However, the benefits for the communities throughout the region are equally significant. Most importantly, the proposed development results in reduced costs for waste management and eliminates the need for landfill disposal of municipal solid waste. Other than avoiding the potential for widespread pollution and contamination of exceptionally pristine natural environments, the region would avoid the need to find adequate sites and construct new landfills every 20 years, which is due to happen in the case of the existing waste management system. More importantly, the proposed development would result in 50% savings in municipal solid waste management investment capital needs. In the business as usual scenario, the region would have to spend approximately \$1,224 per ton of waste in order to dispose of municipal solid waste in landfills, while in the case of the proposed development, waste disposal costs drop by 53% to \$583.3 per ton of waste.

Disposing solid waste in landfills, however, not only introduces health and occupational hazards, but also minimizes the useful operational lifetime of the disposal sites. According to the results of the assessment, in the case of the proposed development the existing landfill sites will be enough to satisfy any need for disposal of residual municipal solid waste for 360 years on average (Table 19). In the case of Limnos, for instance, the existing landfill could remain operational for more than 600 years. Therefore, if the proposed development were to be revamped to continue operations after the end of its useful time, the region could avoid the construction of 56 landfills and spending approximately \$600 million of capital. In any case, during the 50-year analysis period, the region would avoid the

construction of 8 landfills and spending approximately \$140 million. Given the considerable problems, as well as subsequent project delays, that arise every time a new landfill site has to be found due to community concerns and land ownership issues, the region would not only avoid spending capital that could be invested in other sustainable development initiatives, but also avoid time-consuming procedures that galvanize social unrest.

Table 19. Remaining landfill years with and without the proposed development.

Island	Remaining Landfill Years	Remaining Landfill Years with Proposed Development	Avoided Landfills		Avoided Investment Capital (\$ million)	
			Over Analysis	Landfill End of Life	Over Analysis	Landfill End of Life
Lesvos	14	280	2	14	47.8	334.6
Chios	18	360	2	18	29	90
Limnos	32	640	1	16	9.5	152
Samos	8	160	3	8	28.56	76.16

A 20-year lifecycle is assumed for landfills in Samos, Chios, and Lesvos, and a 40-year lifecycle for landfills in Limnos.

Currently, communities cover municipal solid waste management costs through designated taxes and charges, while the average disposal cost ranges from \$49.3 to \$179 per ton of solid waste, depending on the location of the community as well as the distance to the disposal site. With the proposed development, every community throughout the region of

North Aegean would have to pay a set amount of \$49 per ton of waste, which is the average landfill gate fee used for this analysis including an average waste transportation fee of approximately \$18.56 per ton of waste. As such, some communities would avoid paying more than \$100 per ton of waste and a considerable amount in taxes (Table 20).

Table 20. Municipal waste disposal costs with and without the proposed development.

Island	Current Solid Waste Disposal Costs (\$/ton)	Solid Waste Disposal Costs with the Proposed Development (\$/ton)
Lesvos	49.3 – 86.5	49
Chios	49.3 – 179	49 – 67.56
Limnos	49.3 – 134.85	49 – 67.56
Samos	49.3 – 86.5	49 – 67.56

Estimates include values for both municipal solid waste transportation and disposal.

The proposed development would also foster the production of considerable amounts of renewable energy at a lower price compared to the existing methods. Electricity production would be enough to power approximately 1,600 households around Mytilene, Lesvos, in the Enerkem case and 7,8000 households in the ENERGOS case, increase Lesvos' total annual renewable energy generation by 25%, and enhance the overall share of energy from renewable sources from 16.32% to 23.20%. More importantly, the region would gain approximately \$72.51 million, or \$6 million in net present value, because of the drop in electricity prices. Generated electricity would be sold at \$191.5 per MWh, which is 13 %

cheaper compared to the current average market price of \$220 per MWh. As such, the average price of electricity would drop from \$220.68 to \$219.28 per MWh. Furthermore, the proposed development would also help the regional grid to sustain the substantial pressures during the periods of highest energy demand and avoid blackouts in a cost-effective way, since it would operate continuously throughout the year, thereby enabling the displacement the most expensive MWh's that are commonly produced during peak demand.

The Enerkem waste-to-biofuels gasification plant not only presents the most economically, socially, and environmentally advantageous solution but also introduces multiple opportunities for synergies with several sectors of the local economy at the regional scale (Table 21).

Table 21. Synergies with the regional economy.

Sector	By-Product Exchange	Service
Transportation (both inland and among islands)	Bio-diesel, hydrogen	Fuel, gas for vehicles, buses, and ferries
Energy Industry	Bio-diesel, electricity, steam	Energy, transportation
Heavy industry, infrastructure	Fuel, steam, residuals	Energy, aggregate, water
Agriculture	Nitrogen, sulfur, inert residuals, fuel, water	Energy, nutrients, products, fertilizers, landscaping
Tourism	Heat, electricity, fuels	Cooling, heating, energy
Construction	Inert residuals, slag	Aggregate, noise barriers

Among the most significant synergies is the potential to supply the regional transportation fleet with renewable biofuels, further reducing the region's adverse dependency on imported petroleum products and fossil fuels. Given that a typical Enerkem

facility is able to supply enough fuel for 400,000 cars running on a 5% ethanol blend (Lynch, 2015), the proposed development would be able to provide the entire regional fleet, including buses, taxis, and ferries, with renewable biofuels. This would help satisfy the European Union's biofuels mandates for the transportation sector in the region of North Aegean, which specifies that at least 10% of the transportation sector should run on renewable fuels (Council Directive 2009/28/EC, 2009).

Specifically, Lesvos, Chios, Limnos, and Samos import approximately 165, 80, 100, and 97 thousand gallons of diesel and gasoline annually, respectively, in order to fuel their public transportation sectors (Economic Committee of Municipality of Limnos, 2014; Municipality of Samos, 2014; Fafalios, 2014; Kyriakis, 2015). As such, just 4.42% of the proposed development's annual biofuel production would be enough to satisfy these requirements on a yearly basis, while 0.442% would be enough to satisfy the European 10% renewable energy in transportation mandate.

Additionally, the European Commission recently established the first ever legal framework for second-generation biofuels, which specifies that at least 0.5 % of the national biofuel share should originate from advanced second-generation biofuels, such as waste-to-biofuels (EurObserv'ER, 2015). As such, the proposed development would be enough to help the region meet the targets of this mandate as well. In the business as usual scenario, the region would have to rely on imported biofuels to satisfy these requirements.

Furthermore, the facility's excess heat would be utilized to provide energy to adjacent industrial, residential and tourism establishments, and inert residuals, char and water would be used as feedstock for landscaping purposes, as well as construction material for aggregate production and noise barriers. Hydrogen can be separated for use in fuel-cells or for storage

to power other remote entities, such as cars and vehicles for public transport. Importantly, water by-product production would be enough to satisfy the annual irrigation needs of a small community of approximately 1,000 residents. Therefore, several planned small-scale desalination projects could be avoided, now or in the future, in communities that face regular water shortages, such as Moudros and Plati in Limnos. Aggregate production would introduce additional benefits for Limnos and Samos, since the local extractive industry currently lacks facilities to produce aggregate and construction materials, which forces some communities in these islands to rely extensively on imported products to support construction developments at considerably higher prices.

It is important to note that significant amounts of inert residuals and water would be produced through the gasification process, the sale of which could add additional sources of revenue. However, given that establishing long-term contracts for the sale of such products is more complicated compared to establishing energy and waste management contracts, these were not incorporated in the financial assessment.

In addition to the financial benefits from an investment point of view, the proposed development would lead to significant economic, social, and environmental benefits for the communities throughout the region, which are usually excluded from similar analyses in the literature. As illustrated in Figure 17, the environmental and social parameters significantly enhance the feasibility of the proposed development through additional revenue streams of up to \$330 million in net present value in the Enerkem case, and up to \$200 million in the ENERGOS case. This is enough to increase the overall financial feasibility of both evaluated alternatives by more than 100%. In addition, the potential introduction of the anticipated tax scenario on landfilling practices and on carbon emissions, which was investigated through

sensitivity analyses, amplifies the feasibility of the proposed development and the economic unsustainability of the existing system. The landfill and carbon taxes would add approximately \$563 million and \$306 million, or \$61.7 million and \$38.7 million in net present value, of costs, respectively, which would increase the total net costs by 66% over the analysis period. In total, approximately \$1.6 billion of capital, or \$250 million in net present value, would be lost in case the region follows the existing approaches.

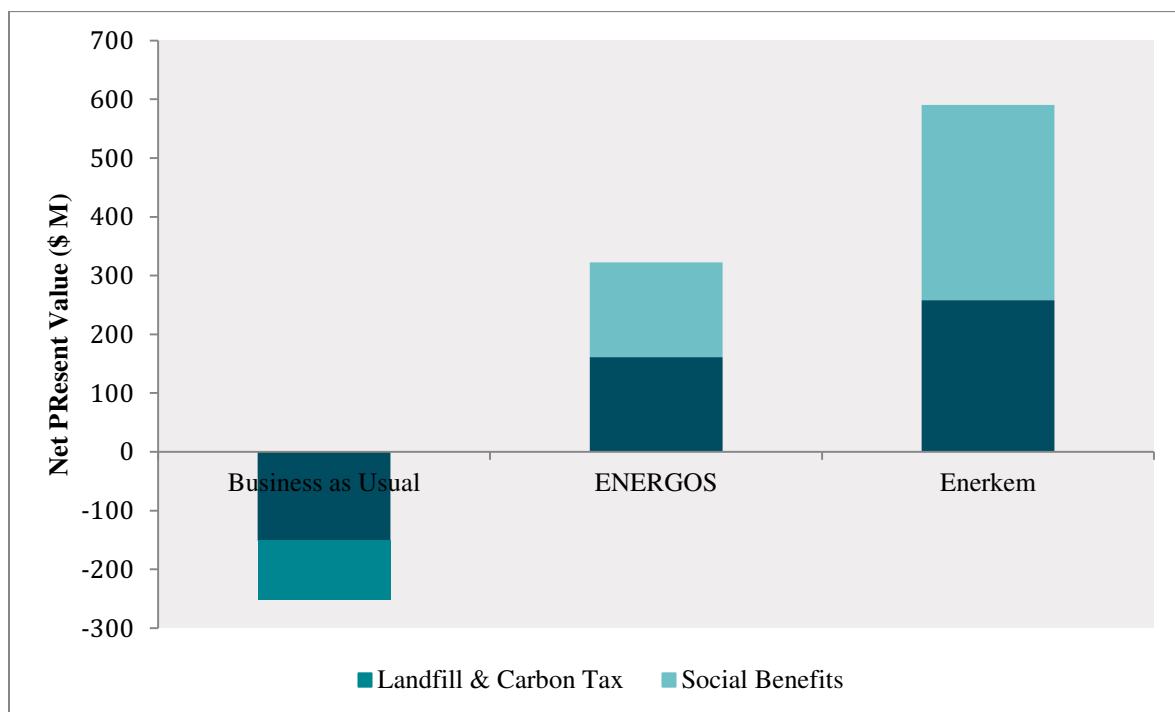


Figure 17. Overview of the best case scenario.

Implications for Policy Making

The results of the analysis highlight the importance of planning at the regional scale as well as the influence of prudent policy making in developing sustainable circular economies in island environments. The implications for policymaking regarding waste and

resource management in island regions with more than one island are especially significant, since the analysis revealed that when synergies are facilitated among and within islands, the novel sustainable waste management network not only minimizes environmental impacts and disposal costs, but also enhances the quality of life of the people and results in substantial social and economic benefits for the region at large.

The sensitivity analyses underscored the particular significance of policy instruments in regards to waste management. Sustainable waste management policies, such as a tax on landfilling practices, although do not directly enhance the feasibility of any proposed development, are influential in making the existing system incrementally unsustainable. As long as the most inefficient and polluting means of waste management remains relatively cheap without reflecting the true costs to the regional communities, innovative waste management plans will continue to face challenging roadblocks. However, other than restricting landfill disposal of biodegradable and recyclable waste, fiscal instruments should also be targeted to promote the development of markets and synergies that utilize secondary materials and by-products, as well as recognize and reward the potential of co-processing and symbiosis at the regional scale. Importantly, similar fiscal instruments and policies have been fundamental in driving the shift towards more sustainable waste, energy and resource management solutions in developed countries throughout the world, which further emphasizes that planning and policy making should be given equal importance.

Most importantly, the proposed development and policy actions can be applied to every island community throughout the world with similar waste generation levels and challenges with regard to natural resource management. Although considerable industrial infrastructure is not a prerequisite, the bigger the industrial activity the larger the variety of

waste generation that can be utilized by any proposed development. Island regions with unsustainable waste management systems based on inefficient landfills, which also rely on imports to satisfy their energy and transportation needs are likely to see substantial benefits.

The important first step is to promote resource management at the regional level by evaluating the challenges and opportunities of each distinct island. Synergistic ways to take advantage of those opportunities and links among the waste, energy, transportation and other sectors of the economy at the regional scale can then be established. In the region of North Aegean, for instance, although waste management is evaluated at the regional level, comprehensive plans are limited to individual islands. Synergies are not sought between and among the islands, resulting in a large number of small-scale inefficient waste treatment facilities that exacerbate collection, disposal and treatment costs, as well as a considerable amount of by-products and residual waste that remain unutilized.

The potential benefits and synergies increase when island regions have more than one island facing waste management and energy issues. Furthermore, groups of islands located at shorter distances, such as the Cyclades region in Greece or the islands in the Bahamas archipelago, also benefit from minimized transportation distances and optimized logistics, thereby further enhancing the potential for sustainable waste, energy, and natural resource management at the regional scale.

Best efforts notwithstanding, several scenarios were not investigated in this analysis, which could further enhance the feasibility of the proposed development and lead research to new levels. First, further work could focus on investigating the profitability of larger developments and the potential for synergies with wastewater treatment and management, as well as other renewable energy and water generation technologies. For example, Lesbos,

Chios, Limnos, and Samos could benefit from utilizing their considerable geothermal resources, which could be combined with a larger development to facilitate large-scale district heating and cooling networks, as well as renewable energy and fuel generation. Moreover, research could focus on investigating the potential of further processing methanol and ethanol in order to produce additional chemicals and additives. Given the considerable market size of most chemical products, sustainable chemical production is likely to be the most significant source of revenue. Last but not least, although sustainable waste management policies result in significant benefits, research should focus on evaluating who and in what way covers these costs, and whether adding incremental taxes in a region that has seen taxes increase by more than 100 % during the last five years would be socially sustainable or not.

Towards a Symbiotic Network of Islands

The development of a gasification facility for waste management in the region of North Aegean Sea would eliminate the need for landfilling of municipal solid waste in all major islands, significantly reduce the need for fossil fuel imports, provide valuable income and jobs for local populations currently struggling with unemployment, as well as facilitate the move towards a circular economy at the regional scale. Results show that the Enerkem waste-to-biofuels plant is the most economically, socially, and environmentally feasible alternative solution. When compared with the business as usual system for waste management and energy generation, the proposed development not only complements the current regional development plans, but also results in regional economic and social benefits of more than \$5 billion over the duration of the analysis. Sensitivity analyses revealed that

under certain conditions and scenarios, the proposed development could be more than five times more cost-efficient compared to the current practices.

Although the proposed development facilitates more sustainable waste management and energy generation practices, it can be used as a starting point for developing a wider symbiotic network that increases recovery of valuable materials and reduces consumption of raw materials and fossil fuels at the regional scale. Biofuel production from the proposed development, for instance, is enough to provide the entire regional transportation fleet, including sea and land transport vehicles, with renewable biofuels. Despite the significant benefits from an investment perspective, as well as for the region of North Aegean at large, the literature currently lacks studies that assess the benefits and costs of regional symbiotic developments in island environments.

Given the region's considerable geothermal potential, significant opportunities exist for the development of large-scale district heating and cooling networks. The potential for district energy and heating evaluated in this analysis could complement and further support systems at a larger scale, able to heat and cool considerably larger population centers. Despite the substantial benefits that could materialize because of this large shift from fossil to renewable energy usage, the potential for such developments in the region of North Aegean Sea has not been researched so far. Moreover, given the region's substantial residual agricultural and biomass production that currently is disposed of in landfills, the potential for the combined effect of the production of biofuels from both the proposed facility as well as through other means could lead to considerable benefits and further foster the decarbonization of the regional economy.

The proposed development can be established in other groups of islands faced with waste management and energy challenges and similar waste generation rates throughout the world. Waste, energy, transportation, and environmental policy makers can use the results of this analysis to develop integrated solutions to island sustainability problems. Although future research could focus on investigating the feasibility of developments with larger capacities, which would be optimal in island regions with larger populations, the proposed development of this research would lead to similar benefits when evaluated in island regions with comparable waste generation rates. Future assessments could investigate the potential for additional synergies with other renewable energy technologies applicable at the island scale, to further unlock symbiotic opportunities for resource efficiency and sustainable natural resource management.

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